OPERATIONAL CONSIDERATIONS OF TRANSITIONING TO EMERGING ULTRA-LOW EMISSION LOCOMOTIVE TECHNOLOGIES FOR HEAVY-HAUL FREIGHT RAIL APPLICATIONS

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SUMMARY

To reduce transportation emissions in certain urban areas, railways in North America may be faced with the challenge of integrating dedicated regional fleets of alternative fuel locomotives into the mainline heavy-haul freight rail network. Regional fleets of alternative technology locomotives introduce various operational issues as locomotive exchanges are added to mainline train runs through urban areas. Four potential technologies to reduce emissions are examined from an operational perspective: diesel-electric with after treatment, liquefied natural gas, diesel hybrid with battery tender cars, and electrification. Each technology is applied to three case studies of heavy-haul bulk unit train operations into an urban area with emissions restrictions. Each scenario involves different commodities and shipment distances. The emissions, energy use, energy cost, and fleet size required for each scenario are presented to illustrate the impact of limiting rail interoperability on the heavy-haul freight rail industry in North America.

1 INTRODUCTION

In recent decades, North American freight railroads have made tremendous improvements to increase fuel efficiency and reduce locomotive emissions. These improvements have been driven by a combination of industry desire to reduce operating expenses, federal regulations and environmental stewardship. Current United States Environmental Protection Agency (EPA) Tier 4 emissions standards for newly manufactured locomotives may represent the practical minimum levels achievable by conventional diesel-electric locomotives [1]. Further freight rail emissions reductions beyond Tier 4 may require on-board after-treatment systems or a shift to an emerging alternative ultra-low emission locomotive technology.

In United States environmental law, a “nonattainment area” (NAA) is a geographical area considered to have air quality worse than the National Ambient Air Quality Standards as defined in the Clean Air Act Amendments of 1970. NAA’s must have and implement a plan to meet the standard, or risk losing some forms of federal financial assistance. Since transportation is major source of emissions in these areas, there is much focus on reducing emissions from all forms of transportation, including heavy-haul freight rail operations, within these locales [2].

Substantial reductions in freight locomotive emissions have been achieved within certain urban non-attainment areas via the deployment of new locomotive technology in captive yard and terminal switching service [2, 3, 4]. However, these alternative-technology locomotives rarely travel more than a few miles from their home facility (where specialized fuel and servicing infrastructure is located) or never leave the NAA. Implementing new low-emissions locomotive technology within a small geographic footprint eliminates many of the operational challenges associated with more widespread use across the rail network. Such deployments of new technology to yard and terminal switching service also fail to fully address the bulk of rail emissions; studies have shown that the majority of freight rail emissions are from line-haul operations [1]

Reducing the emissions of line-haul mainline freight rail operations within the same urban nonattainment areas poses a much more difficult operational challenge for the rail industry. Unlike local yard assignments with their small dedicated group of locomotives, a line-haul freight train operating through a NAA may draw upon a pool of several thousand locomotives from within the North American fleet of 29,500 diesel-electric locomotives. Under current locomotive assignment practices in North America, specific reductions in emissions from line-haul freight operations in NAAs can only be guaranteed if a substantial portion of the fleet is converted to low-emission technology.

The economics of large-scale locomotive replacement suggest a phased transition to new technologies is the only feasible option. The practicalities of developing energy supply and fuelling infrastructure to support a phased transition to new technologies may dictate that initial line-haul operations with new a locomotive technology are confined to portions of the freight rail network in NAAs. In this case, a regional fleet of low-emission locomotives dedicated to mainline operation within a certain region may be necessary.

The presence of dedicated (or “tethered”) regional fleets within each NAA introduces a major obstacle for line-haul freight operations. With only a small fleet of low-emissions locomotives dedicated to operation within the NAA, and trains only using conventional diesel-electric technology outside the NAA, each mainline train must execute a locomotive exchange at the boundary of the non-attainment area as it enters and leaves the low-emissions zone. Such mid-route locomotive exchanges are very rare in the context of North American freight railroad operations. The need to exchange locomotives mid-route will introduce delay and disrupt the seamless movement of freight. The direct cost of delay to trains at locomotive exchange points, and the resulting potential for a shift of time-sensitive freight to the highway mode due to this delay, is often cited as an impediment to deployment of new locomotive technology [5]. In Europe, where locomotives are often exchanged at national frontiers due to incompatible traction power and signal systems, locomotive exchange delay is cited as one reason for the relatively low freight rail market share [6, 7].

Bulk commodities transported by heavy-haul railways are not as sensitive to delay-based mode shift as other types of freight because of the low cost of rail transportation and current U.S. highway truck size and weight regulations [8]. However, delays will still have a negative effect on heavy-haul railway operations by extending equipment cycle times and hindering capacity on routes transiting the NAAs. The heavy-haul railroads will also be required to invest large amounts of capital to purchase new locomotives, construct the locomotive exchange terminals, and establish a new distribution network for the appropriate alternative fuel or energy source.

Heavy-haul routes transiting NAAs must be evaluated to determine the most economically viable manner for deploying new locomotive technologies. For shorter route lengths, despite the poor locomotive utilization, dead-heading conventional and new technology locomotives across route segments where they cannot operate may be more economical in the long term than constructing an exchange facility and being subject to locomotive exchange delays. As the length of haul increases, the operational cost of dead-heading locomotives or hauling heavy tender cars long distances at poor utilization could outweigh the negative impacts of delay and the cost of exchange facilities, making a locomotive exchange the more attractive option. The critical length of haul at which the economics change may be a function of the particular low-emission locomotive technology being considered.

As a step in developing a framework to fully evaluate the economics of locomotive exchange points, this paper will seek to evaluate the impact of a non-attainment area on example heavy-haul freight rail movements in North America. Several emerging locomotive technologies will be applied to three case study heavy-haul freight rail operations involving different commodities and lengths of haul. The case studies will examine the emissions benefits, fuel/energy operating costs, and locomotive capital costs for each technology while illustrating the varying challenges between short and long-haul operation.

2 TECHNOLOGIES UNDER STUDY

This paper examines four locomotive technologies that may potentially operate at emissions levels below the current “conventional” Tier 4 diesel-electric locomotives:

- Tier 4 diesel-electric with after treatment
- Liquefied natural gas with fuel tender
- Hybrid with battery tender cars
- Electrification

Currently, each of these technologies are at varying stages of research, prototype development or commercial implementation. Several recent locomotive technology reviews [1, 9, 10] and tests [11] have evaluated the ability of each technology to reduce emissions in a theoretical or controlled operating environment. The following sections provide a brief overview of each technology with a focus on its practical application to heavy haul freight operations. Of particular interest to this study are the associated emissions, efficiency, cost, and power capabilities.

2.1 EPA Tier 4 with After-Treatment

In order to exceed EPA Tier 4 emissions standards for line-haul freight locomotives, manufacturers of conventional diesel-electric locomotives are exploring new engine exhaust after-treatment systems [12]. Specific technologies include Diesel Oxidation Catalysts (DOC), Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR] and Diesel Particulate Filters (DPF).

Depending on the exact combination of technologies selected, the locomotives with after-treatment may experience slightly higher parasitic loads necessary to power additional on-board equipment such as pumps and fans. This may result in a slight increase in fuel consumption for Tier 4 diesel-electrics with after-treatment systems.

To meet Tier 4 standards, the improved diesel-electric locomotives must, relative to Tier 2 levels, reduce hydrocarbon emissions by 53 percent, NOx by 76 percent and particulate matter by 70 percent. After-treatment will not decrease CO_2 or CO emissions [13].

After-treatment technologies may be available on newly manufactured diesel-electric locomotives or as retrofit kits to modify existing diesel-electrics as they are rebuilt. Retrofit applications are physically constrained by the limited space available for new systems within the locomotive hood. In many instances, retrofits will require substantial modifications to existing locomotives.

Existing locomotives, valued at approximately $2.3 million for AC traction units and $1.8 million for DC traction units can both be retrofitted to accept the after treatment. As no new fuelling infrastructure is required, the major infrastructure cost for this technology is that associated with the distribution network for after treatment chemicals such as urea. The cost of a nationwide infrastructure to supply urea to the entire locomotive fleet has been estimated at $1.5 billion [14].

Current prototype Tier 4 locomotives with after-treatment are able to develop levels of horsepower and tractive effort required to support one-for-one replacement of conventional line-haul diesel-electric locomotives. As currently being tested, the after-treatment technologies are self-contained within the locomotive and do not require tenders or other support railcars.

2.2 Liquid Natural Gas (LNG) with Fuel Tender

The current low cost of natural gas relative to diesel fuel has led to renewed interest in the use of LNG as a fuel for internal combustion locomotives [15]. In addition to manufacturing new locomotives designed for LNG, existing conventional diesel-electric locomotives can be converted to burn LNG using retrofit kits.

LNG has approximately 60 percent of the energy density of diesel fuel. Thus, a volume of LNG equivalent to a typical locomotive fuel tank will only provide a fraction of the range of a diesel locomotive [16]. An LNG tender car is required to supply the volume of LNG required to provide an acceptable range for a line-haul freight locomotive. The LNG fuel tender consists of an insulated cryogenic tank for storing the LNG and other equipment used to convert the LNG to a gas for delivery to the locomotive and combustion [17]. As currently being tested, each tender can supply LNG to the two locomotives it is coupled between; LNG cannot be passed through a locomotive to reach other locomotives in the train consist not directly coupled to a tender. LNG must also be fed from the rear of the locomotive. These restrictions on the placement and orientation of locomotives and tenders impose an operational challenge on the train make-up process.

Since LNG locomotives utilize the same traction system and have the same relative combustion efficiency as conventional diesel locomotives, overall energy consumption will be very similar to current conditions.

The emissions benefits of LNG in line-haul freight service are still unclear. Results from LNG tests conducted in 1991 on 3,000-horsepower mainline locomotives do not offer a good comparison to modern Tier 2 diesel-electric locomotives with higher base fuel efficiency [18]. Current LNG prototypes under test may provide more insight on benefits in line-haul service. Canadian National Railway is testing currently testing retrofitted diesel-electric locomotives. The LNG conversion kit uses a 90-10 LNG diesel mixture and is projected to decrease CO_2 and NO_x emissions by 30 and 70 percent respectively. [19]

Liquefaction of LNG from supplied natural gas is an energy-intensive process. A major liquefaction plant can draw over 100 MW of electricity with its associated generation emissions [20]. Emissions benefits from LNG can also be reduced by LNG leakage into the atmosphere. Methane, the primary constituent of LNG, is approximately 30-times more potent as a greenhouse gas compared to carbon dioxide. How this will be accounted for by the EPA in NAAs is currently unclear.

To implement LNG locomotive technology, railroads will need to purchase new purpose-built LNG locomotives or retrofit kits for current diesel locomotives. One manufacturer estimates the cost of an LNG retrofit kit at $400,000 per line-haul freight locomotive (the cost of, 2013). The railroads must also purchase a fleet of LNG tenders at an estimated cost of $1 million each. [20] A minimum of one tender is required for every two locomotives running on LNG.

Implementation of LNG will also require capital investment in a natural gas supply infrastructure that may include fuelling stations, liquefaction plants and pipelines. A single-consist LNG fuelling station is estimated to cost $700,000 plus the cost of supplying LNG fuel to the station [21]. At locations of high demand, railroads may elect to invest capital in liquefaction plants fed from pipeline connections. However, the capital cost of a LNG liquefaction plant is approximately $1 billion per million tons of annual LNG liquefaction capacity (1 million tons of LNG per year is enough to fill 52 tender cars per day at 30,000 gallons per tender). Thus, it is more likely that LNG will be supplied by third-party liquefaction plants with the cost of liquefaction included in the delivered cost of the fuel as an operating expense.

Relative operating costs of LNG locomotives will be less than conventional diesel provided that the delivered cost of LNG remains below diesel fuel.

Current prototype LNG locomotives are able to develop levels of horsepower and tractive effort required to support one-for-one replacement of conventional line-haul diesel-electric locomotives. LNG locomotives require tender cars that will increase the length and tare weight of trains without adding revenue. Tender designs under development and in testing are sized such that their range will most closely match conventional diesel locomotives when supplying two LNG locomotives.

2.3 Hybrid with Battery Tender Cars

When mature as a technology, hybrid locomotives with battery tender cars have the potential to be the railway equivalent of the plug-in hybrid electric light-duty passenger vehicle. As currently envisioned, the technology concept consists of a railcar filled with batteries that is fully charged at a servicing facility before each train run. When coupled together, the pre-charged battery tender can supply a properly equipped A.C. traction diesel-electric locomotive with electricity for traction power on a mainline haul without the need for any wayside power supply infrastructure. While the locomotive is drawing power from the battery tender, the diesel prime mover can be idled or shut down, saving diesel fuel and reducing mobile source emissions. Outside of the non-attainment area, the hybrid locomotive can operate as a conventional diesel-electric locomotive without any need for the battery tender.

A locomotive equipped with a battery tender may produce no mobile source emissions when operating in battery mode. By eliminating the combustion process, the efficiency of the fully electric traction system allows for a significant reduction in purchased energy for every gallon of diesel avoided.

Current battery tender car design concepts claim a storage capacity of 5 MWh of electricity, sufficient power to provide an average of 160,000 ton-miles of freight rail transportation on a single charge [22].

The number of reduced-emission miles and gallons of diesel avoided may be increased through battery-tender storage of electricity from regenerative braking. The exact benefits of recovering braking energy will vary under different combinations of locomotive duty cycle, operating speed and grade profile. Given the efficiency of the electric traction system to generate braking energy and then consume it again, multiplied by the efficiency of the battery storage system, less than 55 percent of the energy used to accelerate a train or overcome grade resistance can be used during the next acceleration cycle or grade ascent given an ideal duty cycle and grade profile. When the energy consumed overcoming inherent train resistance is factored into the calculation for a more realistic duty cycle on a route with more level terrain, potential reuse of regenerative braking energy drops quickly [23]. Locomotive manufactures claim that depending on the exact route and duty cycle, only 10 to 30 percent of diesel gallons can be avoided through energy regeneration. [24, 25, 26]

Although the battery tender car concept may allow for operation with zero emissions directly from the mobile source, the batteries must be charged with electricity drawn from the regional power grid [27]. Thus, the actual emission savings are a function of the regional electric source generation profile.

According to one supplier, the initial cost of each conceptual 5 MWh battery tender car is estimated at $5 million [23]. Since the cost of the tender is largely driven by the cost of the batteries, costs could decrease over time with improved battery technology and as economies of scale are gained.

Over the life of the battery tender car, the batteries will need to be replaced to maintain peak performance. Battery life is estimated at 3,000 cycles before replacement. Based on communications with suppliers, it is anticipated that over a 15-year period, battery replacement will add $6 million to the cost of each tender [23]. Operating cost savings will depend on the number of battery miles and the relative cost of electricity and diesel fuel. Railroads will also need to invest in electrical charging infrastructure for the battery tenders.

One-for-one replacement of conventional diesel-electric locomotives with battery-tender-equipped locomotives is possible. However, the range of the battery tender car is small, limiting the number of reduced-emission miles. The battery tender cars will increase the length and tare weight of trains without adding revenue. Unlike LNG fuel tenders, it is envisioned that a locomotive may draw electricity from multiple battery tenders. Conceptually, it may be possible to configure either end of a conventional locomotive to mate with a battery tender or pass electrical current through to locomotives not directly coupled to the battery tender. This may allow all of the battery tenders to be grouped in one block behind the locomotives, simplifying train make-up.

2.4 Electrification

Electrification involves the transmission of electricity from remote power generation stations to electric locomotives via overhead catenary wire suspended above the tracks. The electric locomotives convert the power supplied by the catenary to the proper voltage for use by the locomotive traction motors to control speed and tractive effort. The ability of electrification to power freight trains has been demonstrated by past use in North America and by its application to heavy haul freight operations in Sweden, Australia, South Africa and India [28].

	Loaded Cars	Tons (tonne)/ Car	HP/ Trailing Ton	No. Loco.	LNG Tenders	Battery Tenders	NAA Miles (km)	Non-NAA Miles (km)	Total
Oil	78	83 (75.3)	2.00	4	4	4	178 (286)	440 (708)	620 (998)
Ore	60	109 (98.0)	0.90	3	3	8	338 (544)	130 (209)	470 (756)
Coal	100	100 (90.7)	0.60	3	3	10	312 (502)	1500 (2,414)	1812 (2,916)

Table 1. Case Study Parameters

Similar to the battery tender cars, electrification eliminates mobile emissions and transfers them upstream to the power generation plant. The emissions associated with electric power supply depend on the regional generation profile. On many electrified railways, using regenerative braking energy from one train to satisfy the power demand of another train is an option to reduce the overall amount of purchased electricity. The lack of on-board storage and the unscheduled nature of North American heavy-haul freight rail operations make it difficult to realize benefits from reuse of regenerative braking energy. Also, the amount of energy and its constantly fluctuating temporal and geographic distribution make it difficult to sell back to the local electric power grid.

Electrification requires a significant infrastructure investment in the overhead catenary traction power distribution system. Recent studies have estimated the capital cost of electrification infrastructure at $4.8 million per track-mile [5].

Operating cost savings will depend on the relative cost of electricity and diesel fuel [15].

One-for-one replacement of conventional diesel-electric locomotives with electric locomotives is conceptually possible if a new generation of purpose-built electric line-haul freight locomotives are developed for the North American market. Current European designs develop sufficient horsepower but lack the number of axles, axle loads and adhesion required to match the tractive effort of a conventional North American diesel-electric locomotive. The electric locomotives do not require tender cars but a locomotive change is required.

3 ANALYSIS

In order to demonstrate the operational consequences of regional deployment of the four emerging locomotive technologies on heavy-haul railway operations through NAAs, three case studies of three different bulk commodities – crude oil, coal, and ore- are developed (Table 1). Each train is travelling to the same destination within a theoretical NAA along unique routes developed from actual railway curve and grade profiles. The origins of the trains vary in distance from the non-attainment area such that each commodity has a specific length of haul (Table 1).

The cars per train, tons per car, and horsepower (HP) per trailing ton are representative of North American heavy-haul freight railroad values. Horsepower per trailing ton is varied to examine how fleet size is impacted depending on the amount of power needed.

The locomotives are all assumed to be equivalent in power and tractive effort to the current North American standard 4,400 hp (3.28 MW) mainline heavy-haul diesel-electric locomotive.

To provide the greatest operating flexibility, one LNG tender is assigned to each locomotive. For purposes of train simulation, each LNG tender is represented as 30,000 gallon tank car with a 286,000-pound (130,000 kg) maximum rail load [28].

The battery tenders are assigned based on their capacity to store 5 MWh of energy (or effectively 160,000 ton-miles of transportation productivity). For example, the oil train requires approximately 580,000 ton-miles within the NAA so four tender cars are required to provide enough storage for the train to traverse the NAA on electricity from the batteries. The battery tenders are represented as typical 50-foot boxcars with a 286,000-pound (130,000 kg) maximum rail load [29].

The case studies all assume a stop at the NAA boundary to exchange locomotives from conventional diesel-electric locomotives to new lower-emissions technology on the loaded inbound trip. On the empty return trip, the unit trains stop at the NAA boundary to exchange the new technology locomotives for conventional diesel-electrics. Tenders are added and removed along with their respective locomotive consists as appropriate. The result is that a portion of the trip in the NAA is a run as “clean” miles using lower-emissions technology while the remaining miles outside the NAA operate in a conventional manner.

The number of “clean” miles in the NAA is different for the route associated with each commodity for several reasons. First, the border for the non-attainment area may not be a uniform radius around the final train destination. The edge of the

	Diesel			LNG			Battery Tender			Electrification		
	NAA	Out	Total	NAA	Out	Total	NAA	Out	Total	NAA	Out	Total
Oil	790	176	966	85	176	261	75	176	251	31	176	207
Ore	2,381	52	2,433	243	52	295	0	52	52	94	52	146
Coal	2,532	733	3,265	265	733	998	170	733	903	100	733	832

Table 2. Energy Consumed per Technology Type (GJ)

NAA may be dictated by pre-established district, county, or other jurisdictional borders. Second, the placement of locomotive exchange facilities at the edge of the NAA could be influenced by specific line characteristics, existing yard/terminal facilities, geographic features and land availability.

In subsequent sections, the energy savings, emissions benefits, and fleet size of each heavy-haul unit train operation is calculated for each technology and compared to the baseline diesel-electric locomotives.

3.1 Energy

The energy used by each train within the non-attainment area is calculated using a train performance calculator (TPC). The TPC uses route and train characteristics to evaluate the energy consumed with the Davis Equation [30]. The route inputs for grade, speed, and curvature are taken from actual U.S. Class 1 mainline routes. The train inputs of weight, size, and aerodynamic drag coefficients are based on railcar type information in the US Surface Transportation Board waybill sample data for similar shipments and coefficients in the AREMA Manual for Railway Engineering [30, 31]. The energy used for the remaining route length outside the NAA is estimated using industry averages for fuel consumption of similar bulk unit trains [32]. Since the TPC provides energy consumption given the efficiency of a diesel-electric locomotive, the energy used by the electric locomotives is calculated based on the relative efficiency of the two types of motive power [33].

Table 2 shows total energy used per round trip train run and the portion of the energy that is consumed inside and outside the NAA. The data is presented in gigajoules (GJ) allowing for a like to like comparison of both the energy consumed by the different technologies but also the energy used for each individual case study. For example, The LNG case involves two different fuels, with LNG inside the NAA and diesel fuel outside. This makes it difficult to present one total fuel consumption value in gallons for the entire route. This also raises another operational consideration: fuelling infrastructure will need to handle both diesel and LNG.

In this case, the values for diesel represent both the base case of conventional diesel-electric locomotives and the tier-4 with after treatment as it is assumed that the after treatment does not substantially affect efficiency.

The TPC also has the capability of calculating the regenerative braking potential for a given route. A

	Diesel			LNG			Battery Tender			Electrification		
	NAA	Conv.	Total	NAA	Conv.	Total	NAA	Conv.	Total	NAA	Conv.	Total
Oil	10,234	22,767	33,001	7,164	22,767	29,931	-	34,426	34,426	-	27,610	27,610
Ore	30,831	6,740	37,571	21,581	6,740	28,322	-	6,764	6,764	-	21,331	21,331
Coal	32,794	94,872	127,666	22,956	94,872	117,828	-	121,314	121,314	-	110,392	110,392

Table 3a. Kilograms CO2 Emitted per Roundtrip

Oil	29	65	95	9	65	74	-	66	66	-	66	66
Ore	89	19	108	27	19	46	-	19	19	-	20	20
Coal	94	273	367	28	273	301	-	273	273	-	273	273

Table 3b. Kilograms NO_x Emitted per Roundtrip

Oil	0.44	0.98	1.42	12.07	0.98	13.05	-	1.85	1.85	-	1.34	1.34
Ore	1.33	0.29	1.62	34.43	0.29	34.72	-	0.29	0.29	-	1.38	1.38
Coal	1.41	4.09	5.51	37.55	4.09	41.64	-	6.06	6.06	-	5.25	5.25

Table 3c. Kilograms PM Emitted per Roundtrip

portion of this regenerated energy is subtracted from the total consumption for the battery tender locomotive case because of its capability to store and reuse power. The route profile of the ore train in the NAA allows it to take advantage of this capability to consume very little energy within the NAA.

3.2 Emissions

The technologies are evaluated for their carbon dioxide (CO_2), particulate matter (PM), and the mono-nitrogen oxides (NO_x) emissions within and outside of the NAA (Tables 3a-c)

The diesel-electric emissions are estimated using averages from the EPA and the energy consumed for each train (Table 2) [13, 34].

The battery hybrid and electric locomotives do not have any mobile emissions within the NAA. However, the emissions related to electric power generation at a remote location are accounted for in the total outside of the NAA. The average power generation mix for the U.S. is used to calculate the emission factors [31].

Based on current tests, the LNG emissions are reduced by 30 percent for CO_2 and by 70 percent for NOx [18].

Diesel-electric locomotives are used in all cases outside of the NAA. As stated earlier, it is assumed that the train will execute a locomotive exchange and not dead-head the unused power or tender cars where they are not needed.

LNG, battery tenders and electrification all reduce emissions within the NAA. From a global perspective, however, the overall emissions reduction for LNG is only 10 percent In terms of total emissions. Similarly, although the battery tender and electrification eliminate all emissions within the NAA, they show global emission reductions of less than 10 percent, Although battery tenders benefit from regeneration energy storage and both electric options benefit from the efficiencies of centralized electricity generation, the of coal-fired power plants in the U.S. tends to offset emissions benefits.

3.3 Operating Cost and Delay

For the purpose of this study, the operating cost for each unit train cycle is sum of the fuel cost per round-trip and the delay cost associated with the locomotive exchange.

The 2014 U.S. Energy Information Administration unit cost values for each fuel type are used to calculate the fuel/energy expense based on the calculated consumption in Table 2 [35, 36].

Since it is assumed that the bulk commodities will not experience any modal shift due to train delay, and that the locomotives and railcars are operating in dedicated unit trainsets, the delay cost is crew expense for the extra time spent performing the locomotive exchange. The U.S. national average cost per hour for train crews is $79.53 [37].

The amount of delay experienced by each train at the exchange point depends on the locomotive configuration within the train consist. Conventional trains operating with front-end power only require less time for a locomotive exchange than distributed power configurations. For this study, the oil train is assumed to have a front-end only configuration while the ore and coal trains have front and rear-end distributed power configurations. The former configuration requires one hour for a locomotive exchange while the latter requires two hours. Thus, for a round trip with an inbound and outbound locomotive exchange, the exchange delay associated with the oil train is two hours while the delay associated with the ore and coal trains is four hours per round trip [8].

In addition to the per-hour cost, the delay time could also increase crew cost due to restrictions on crew hours of service. A given crew can only work for a period of 12 hours according to U.S. Federal regulations. Depending on the current crew scheduling, there may be a need to add additional crews to complete the haul if the delay causes them to exceed the 12 hour duty period. Re-crewing a train can be time consuming, expensive, and hurt the capacity of a line if the train is stopped for an extended period of time. Table 4 summarizes the operating cost for each technology.

From a pure operating cost perspective, electrification is the least expensive option. However the expensive and often prohibitive upfront capital cost of overhead catenary is not included. The amount of this cost allocated to each unit train run would vary based on overall traffic levels on each route. LNG is less expensive than diesel but only due to the cost of the fuel. If the margin between the two fuels continues to shrink, LNG may lose its appeal as an alternative fuel source. Again, this comparison does not consider the cost of establishing LNG fuel delivery infrastructure. Like electrification, the cost of these facilities allocated to each unit train would vary based on overall traffic levels.

3.4 Cycle Time and Fleet Size

The delay time associated with the exchange also has an effect on the fleet size required to maintain existing levels of heavy-haul service. Depending on the cycle time of a given consist, the delay could require the operating railroad to purchase another consist to ensure that they do not incur extra delay while waiting for locomotives to return.

	Diesel			**LNG**			**Battery Tender**			**Electrification**		
	Fuel	Delay	Total	Fuel	Delay	Total	Fuel	Delay	Total	Fuel	Delay	Total
Oil	9,524	159	9,683	4,746	159	4,905	11,597	159	11,756	902	159	1,061
Ore	10,843	318	11,161	2,713	318	3,031	2,796	318	3,114	2,713	318	3,031
Coal	36,845	318	37,163	2,893	318	3,211	44,208	318	44,527	2,893	318	3,211

Table 4. Fuel and Delay Cost (USD]

For the operations in the case study, the cycle time is calculated by dividing the total mileage of the round trip by the average network velocity for heavy-haul service. For this case study, the average velocity of coal trains as reported by all U.S. Class was used as representative of heavy-haul bulk train operations [38]. A frequency of two trains per week is assumed. Thus, a given consist must return to its loading origin within 3.5 days (84 hours) or else the railroad will need an extra trainset. As Table 5 shows, before the delay is added, each of the three heavy-haul operations only requires one trainset to satisfy demand. However, once the delay is added, the cycle time for the coal train exceeds 84 hours. In order to accommodate the delay associated with locomotive exchange entering and exiting the NAA, the operating railroad will need to purchase more locomotives and railcars. The associated capital and maintenance costs will increase the overall cost of this heavy-haul operation.

	Cycle Time (hrs)	**Train Sets**	**Exchange Delay**	**Cycle Time* (hrs)**	**Train Sets***
Oil	28.2	1.0	2	31.2	1.0
Ore	21.5	1.0	4	26.5	1.0
Coal	82.6	1.0	4	87.6	2.0

Table 5. Fleet Size Before and After Delay

3.5 Alternatives to Locomotive Exchange

The presented analysis of emissions benefits and preceding discussion of operational issues associated with locomotive exchange suggest that from a global perspective, dedicated regional fleets may not be the deployment strategy preferred by the railroads. To avoid the operational challenge of the locomotive exchange (and the capital cost of the exchange facility), instead of implementing new technology on all trains within the NAA, railroads may be more likely to assign new technology locomotives to a select number of cycling trainsets on fixed routings. These “closed loop” operations will frequently return the new technology locomotives to the NAA for their emissions benefits and to reach their specialized servicing facilities that will not be found elsewhere on the network.

Operation without exchange points presents varying degrees of operational challenges for each technology. Tier 4 diesel with after treatment can operate equally well outside the NAA. LNG can also operate through the exchange point if the fuel tenders can provide enough range for the locomotives to complete an entire round trip (to avoid constructing multiple LNG fueling points at all train origins remote from the NAA destination.

Electric locomotives, however, cannot operate beyond the end of catenary at the edge of the NAA. Since full heavy-haul freight dual-mode locomotives have proved impractical in North America, to avoid a locomotive exchange, the train would need to deadhead electric or diesel-electric locomotives on each route segment. This would impact locomotive utilization with its associated opportunity cost and greatly increase the required fleet size.

The battery power is depleted, hybrid locomotives can operate beyond the NAA on their conventional diesel-electric prime movers. However, if no exchange stop is made, the train must haul the heavy battery tender cars over the entire route while running on diesel as opposed to dropping them off at the edge of the NAA. There is a tender fleet size and opportunity cost to this type of operation along with the extra cost and emissions from hauling the tender car over portions of the route where its functionality is limited.

4 CONCLUSIONS AND FUTURE WORK

Attempting to reduce line haul freight rail emissions in nonattainment areas through dedicated regional locomotive fleets will have an impact on the operations for heavy-haul bulk trains. The technologies available to reduce emissions have varying capital costs and the operating costs are tied to the cost of fuel. While emissions can be eliminated in the NAA using electric or hybrid locomotives, the indirect emissions associated with power generation- especially coal-fired plants- does little to reduce global emissions. Longer cycle times associated with exchanging locomotives at the edge of NAA can impact fleet size and crew scheduling, increasing the cost of bulk freight rail transportation. Although delays are unlikely to trigger a shift of bulk commodities to other modes, they will decrease the ability of the railroads to deliver heavy-haul service in an economical manner.

This paper only examines emissions benefits and operational costs of the new locomotive technologies. This is just one part of a larger framework that also encompasses the capital cost of equipment, energy supply infrastructure and locomotive exchange point track infrastructure to be used to complete a more comprehensive evaluation of the economic benefits and costs of these locomotive technologies for mainline freight rail service in North America.

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