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PROSPECTS FOR DYNAMIC BRAKE ENERGY RECOVERY ON NORTH AMERICAN FREIGHT LOCOMOTIVES

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ABSTRACT

As fuel costs and environmental impacts assume greater importance to railways, so does the importance of options for increased energy efficiency and emissions reduction. A study was conducted on the potential recovery of dynamic brake energy from diesel-electric locomotives in North American freight service. Using computer simulations (Train Energy Model) and locomotive event recorder data, estimations were made of the energy that could be recovered from dynamic brake use. In addition, the differences between the results of the computer simulations with respect to the actual events recorded were examined in order to evaluate how well the model simulates an engineer's operation of locomotives and provide guidance for future improvements to the simulation model.

A case study of the energy recovery potential for a Class 1 railroad operating on a major mountain pass in North America was conducted. The route analyzed has two characteristics that make it a good candidate for studying energy recovery potential. First, there is an extended down grade approximately 25 miles long, and second, it has heavy traffic with about 80 trains a day traversing it. Both of these factors enhance the likelihood that investment in energy recovery technology will be economically viable. It was found that the total dynamic brake energy potential was over 1,200 kilowatt-hours per train. Depending on the efficiency of the storage system, as much as 70 gallons of diesel fuel could be saved per train. This equates to 2,800 gallons of fuel a day and a corresponding reduction in emissions. Never the less, fuel savings themselves do not provide enough incentive to warrant implementation of dynamic brake energy recovery, but with the addition of environmental cost savings financial benefits may be seen.

INTRODUCTION

Each year the Class 1 railroads collectively use over 3.8 billion gallons of diesel fuel [1]. This represents over 10% of their annual operating expenses. With over 500 million train-miles operated a year, even a small percentage decrease in the amount of fuel consumed has a substantial potential for cost savings. A local increase in fuel economy could produce a marked decrease in fuel consumption if it occurred on a suitably busy section of track.

Each gallon of fuel burned also produces air pollutants [2]. The amount and type of these pollutants can be partially controlled through locomotive diesel engine technology, but pollution cannot be eliminated. As combustion temperatures are increased, the production of pollutants such as hydrocarbons, carbon monoxide, and carbon dioxide are decreased, but the production of the oxides of nitrogen is increased [3]. A reduction in the amount of fuel consumed will generally cause a decrease in the amount of all air pollutants produced.

With the dual goals of reducing fuel consumption and locomotive emissions, this paper examines the prospects for recovering and reusing energy from locomotive dynamic brakes. Analysis of the cost savings from reduced fuel consumption and the potential benefits of reduced locomotive emissions was conducted to determine the feasibility of offsetting the costs of construction and operation of an energy recovery system.

Dynamic brakes have been the focus of fuel reduction studies in the past. The fact that dynamic braking produces electricity that is then wasted as heat has drawn scrutiny because of the increase in efficiency that could be realized from reusing this energy. Regenerative braking and energy recovery in electrically propelled trains has long been used in electric trains [4] and is growing in popularity with the mass production of hybrid automobiles [5].

In the 1970's, the oil crisis increased awareness of the issue of fuel efficiency. It was during this period that a large amount of research was conducted on increasing the fuel efficiency of freight trains.

1. PREVIOUS FRA RESEARCH

In 1979, the Federal Railroad Administration (FRA) published two reports on modifying locomotives to recover dynamic brake energy. The first was a study of the feasibility of modifying a diesel-electric locomotive to be able to be powered through the use of electrified catenary wires when the infrastructure was available [6]. The study concluded: (1) such technology is technically feasible, (2) performance while in the electric mode is greatly enhanced without reducing the efficiency while in the diesel mode, and (3) the technology can be used as a means of progressively electrifying a railroad route in order to avoid a large initial capital investment. These conclusions were based solely on examining the feasibility of a dual mode locomotive and not on the feasibility of an electrification or energy storage project.

A second study investigated the possibility of modifying a switching locomotive to be able to store and reuse dynamic braking energy [7]. For the purposes of this study, an EMD SW1500 was permanently coupled to a boxcar that contained a flywheel energy storage system. The locomotive was modified so that whenever the dynamic brake was used, the power coming from the traction motors would be directed to the flywheel storage system instead of through the resistor grids. The energy stored in the flywheel system would then be used to power the locomotive as it ran. When this energy was exhausted, the locomotive would continue to run using power generated by its diesel engine.

After a 16-month trial period, Phase I of the study was completed. The study concluded that the program was technically, but not economically, feasible, and Phases II and III of the program were canceled. Even with modifications to the traction motors and control systems, the system saved little energy. The duty cycle of the switching operations did not provide enough energy recovery from the dynamic brakes.

These two studies showed that modifying a diesel-electric locomotive for use in electrified territory or with train-borne energy storage are technically feasible. With the advances in electrical and locomotive technology that have occurred in the 25 years since these studies were conducted, it is reasonable to assume that these options are still technically feasible.

Together these studies show that a system for recovering and storing the energy produced by dynamic braking could prove to be economically feasible if it was applied to a location where the duty cycle of operations was favorable to producing large amounts of dynamic energy. Out of an initial survey of likely locations, Cajon Pass in Southern California possesses two characteristics that would make it suitable for a system that relied on dynamic brake use. It has long downgrades and a large number of trains pass over it daily.

Cajon Pass is located on BNSF's southern transcontinental line between Barstow, CA and San Bernardino, CA. It is comprised of approximately 25 miles of westward downgrade and 55 miles of eastward downgrade. Locomotives traveling this route can be in dynamic braking mode for over two hours in total.

The duty cycle of trains going down the pass is substantially different from that of the switching locomotive that was studied by the FRA [7]. Although the FRA study concluded that dynamic brake energy storage was not economically feasible for use in switching situations where dynamic brake use is limited, a study of trains that experience long periods of sustained dynamic brake use may prove energy recovery to be feasible.

2. COMPARISON OF EVENT RECORDER DATA AND SIMULATIONS

To analyze the potential for cost effective dynamic brake energy recovery, an estimate of the total amount of energy that could be recovered must first be developed. To address this question, data on the dynamic brake characteristics of trains using Cajon pass were gathered. Use of train simulation software such as the AAR Train Energy Model (TEM) was evaluated as a means of quickly developing large data sets [8].

Prior studies have shown the validity of both the fuel consumption and train handling algorithms contained in TEM [9, 10]. However, the portion of the program that simulates dynamic brake usage and energy production has not been validated. For this simulation software to be used in the analysis of dynamic brake energy production, its validity needed to be assured. Validation of the simulation was conducted by comparing the output of the program with actual train event recorder data. The BNSF railroad provided route data for the Cajon Pass portion of their southern transcontinental main line as well as train consist and locomotive event recorder data for trains traversing this route.

The locomotive event recorder data were gathered from the onboard Wabtec recorders and viewed with Wabtec's event recorder analysis software. These data were analyzed to extract the operating characteristics of the train while it crossed the pass. The event recorder stores data from 36 discrete channels at one-second intervals. The information collected ranges from the status of the engineer's controls (throttle setting, air brake application, locomotive horn, etc.) to internal locomotive parameters (speed, wheel slip, amperage to traction motors and dynamic braking grids, etc.). No data are recorded for the position of the train, so this information must be determined using waypoint timestamps from the BNSF system. Once the time stamps on the event recorder were calibrated against these waypoints, the position of the train along any given portion of its recorded journey could be extracted.

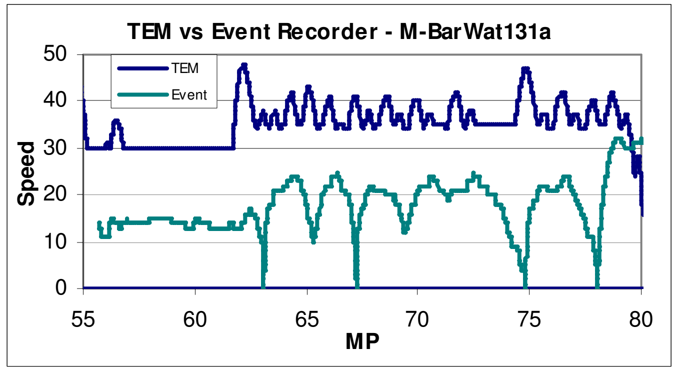
After the determination of a train's location, information such as speed, throttle notch setting, dynamic brake setting, and dynamic brake current was extracted for analysis. The speed and position data were compared with the results of the Train Energy Model (TEM) simulation software. For dynamic brake energy comparisons, TEM reports the quantity of work done by the simulated dynamic brakes in kilowatt-hours (kWh). To determine the amount of work done by the dynamic brakes in the real train, the amperage from the event recorder data was summed to provide a total of amp-seconds for the journey. Using an estimate of the resistance of the dynamic braking grid of 0.4 ohms, the power dissipated through the grids was calculated. Table 1 shows the comparison between simulated and calculated dynamic brake energy dissipation.

	Dynamic Energy (kWh)	
Train Symbol	**Calculated**	**TEM**
M-BARWAT120A	2,592	2,362
M-BARLAC131A	1,244	1,083
M-BARSDG131A	692	968
M-BARWAT131A	2,744	10,204
M-BARWAT130A	155	1,375
M-SDGBAR101A	800	6,100
M-SDGBAR128A	237	3,177

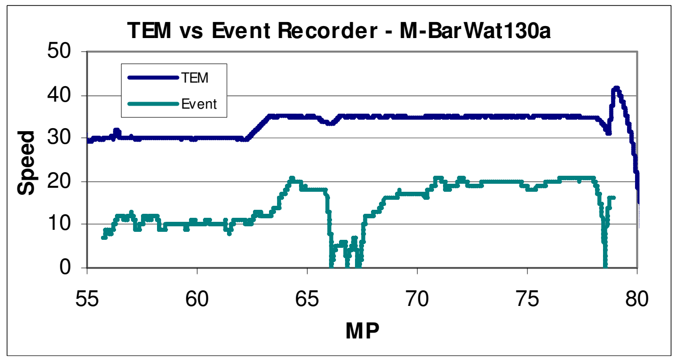
Table 1. Comparison of actual versus simulated dynamic brake energy for seven trains.

The dynamic brake totals for the listed trains exhibit a large variation. These differences can be caused by either the engineer's actions or by system constraints such as slow orders and other traffic on the line.

The TEM simulations assume perfect conditions that allow continuous running at maximum track speed. Also, the simulation software's train handling algorithms attempt to control the train first with the dynamic brakes and using the air brake only when more braking is required [8]. In situations such as this, an engineer's experience in the operation of trains over the specific section of track may cause operational differences that are not represented in the simulation. When the event recorder speed data were plotted against the simulation data, it was evident that there were constraints to the actual train operation that were not represented in the simulations (Fig. 1).



(a)



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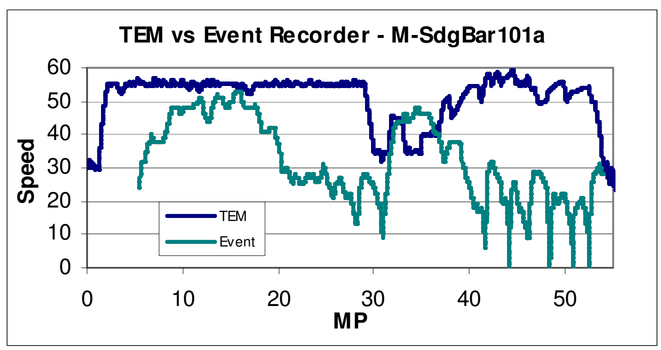

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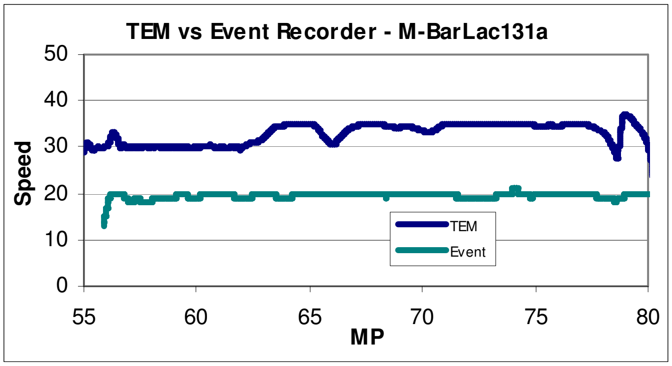
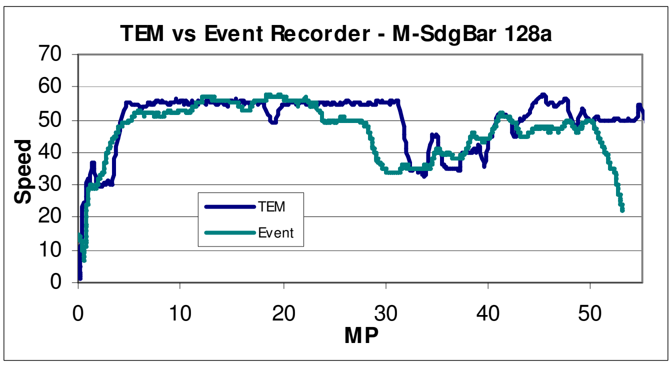


(d)



(e)

Figure 1. Speed profiles for (a) M-BARWAT131A, (b) M-BARWAT130A, (c) M-SDGBAR101A, (d) M-BARLAC131A, and (e) M-SDGBAR128A.

The different values for dynamic brake energy are not correlated to the level of similarity of the two speed profiles for the trains. Trains that had very similar values for dynamic brake energy did not show matching speed profiles (e.g. M-BARWAT131A [Table 1, Fig. 1a]). Also, trains that showed very similar speed profiles did not have similar dynamic brake values (e.g. M-SDGBAR128A [Table 1, Fig. 1e]).

Based on these results, it was concluded that TEM could not be used to reliably simulate the dynamic brake energy. Instead, an empirical approach was used in which dynamic brake data were taken from event recorders. This limited the number of situations that could be analyzed to those for which data were available.

Potential recovery mechanisms

Any device that is used to recover dynamic braking energy must be able to safely handle the amount of energy produced. The types of system used will determine the specifications and cost of the system in question. Onboard battery [11], supercapacitor [12], and flywheel [7] energy storage systems are required to store a lower total amount of energy than their wayside storage counterparts [13] and require a lower capital expense for supporting infrastructure. Wayside storage systems are not limited in their storage capacity by the constraints of train or locomotive size limits and the train environment such as shock and vibration.

The exact type of storage system is not considered in this paper. In the field, the type and size of storage device used will have to be decided based on the balance between total energy stored and cost. The only assumption made is that the recovery, storage, and reuse of this energy will require special equipment or modifications to existing equipment that will be restricted to use on Cajon Pass. This limits the number of trains that would benefit from this type of technology but also limits the number, scope, and cost of modifications needed.

3. FUEL SAVINGS BASED ON DYNAMIC BRAKE ENERGY RECOVERY

The average dynamic brake energy calculated from event recorder data (Table 1) was 1,209 kWh per train. Cajon Pass has an average of 80 trains per day (Table 2). Recovery of energy would require that a storage device or modified locomotive be attached to trains to store and reuse dynamic brake energy. Such equipment would have to be limited to the pass area to maximize utilization and thus minimize capital expense, operating costs, and wayside construction if applicable. Only certain trains would be eligible for use of energy recovery equipment, because of the undesirability of stopping high priority, time sensitive intermodal, passenger and unit trains.

Symbol	Description	Daily Average
A	AMTRAK	2
B	Bare Table Flat	3
F	Foreign Road Train	18
G	Loaded Unit Grain	1
L	Local Switcher	3
M	Merchandise (Regular)	9
P	Premium Intermodal	6
Q	Guaranteed Intermodal	8
S	Stack Train Intermodal	12
U	Non Coal/Grain Unit	1
V	Vehicle (Autos/Parts)	1
Z	UPS - LTL Intermodal	16
	Total:	80

Table 2. Daily distribution of traffic for Cajon Pass

Once these trains are removed from the total, 34 trains a day remain. Using these 34 trains as the basis for analyzing the potential for energy recovery, the following results are obtained (at 100% efficiency): 41,106 kWh/day and 15,000 MWh/year (Table 3). This represents all of the energy expended using dynamic brakes to control down-grade speed.

Recovery Efficiency	Yearly Energy Recovery (MWh)	Fuel Savings (gal)
100%	15,000	1,050,000
75%	11,250	787,500
50%	7,500	525,000

Table 3. Energy recovery potential based on system efficiency.

Using the conversion factor of 70 gallons of diesel/MWh, an ideal fuel savings would be 1,050,000 gallons, which, at $1.50 per gallon translates to an approximate annual savings of $1,500,000.

However, 100% energy recovery efficiency is unrealistic and not all the dynamic brake energy could be recovered. Operational requirements may also make it impossible to switch every standard locomotive out with one that can recover energy. In these situations, the dynamic braking energy of the standard locomotive would not be recoverable. For the purpose of this analysis we assumed an in-service efficiency of 50%. Thus, only about 525,000 gallons of diesel fuel could be saved a year corresponding to an annual savings of $787,500 (Table 3).

This level of yearly savings limits the economic justification for modifications or new equipment purchases. It is unlikely that suitable energy recovery and storage technology could be installed for this amount. Thus, the economic feasibility of a project such as this is not justified on fuel savings alone. However, the environmental benefits of the fuel savings should also be considered in order to fully assess the potential benefits of such a system.

4. ENVIRONMENTAL COST SAVINGS

The United States Environmental Protection Agency (USEPA) publishes various documents that attempt to assign a cost associated with air pollution. The Office of Air Quality Planning and Standards (OAQPS) *Economic Analysis Resource Document* (1999) [14] is provided as a tool to help planners quantify the environmental costs of their current or future decisions. The ranges for the cost of pollutants are given for volatile organic compounds (VOC), particulate mater (PM), and SO_2.

Since the Clean Air Act (CAA) [15] established the framework for an emission credit trading system, the market value for these credits can also be considered as an estimate of the cost of pollution. The CAA allows for four types of emissions credits to be traded. These emissions are VOC, PM, CO, SO_2, and NO_x. The two biggest markets are for SO_2 and NO_X.

Since credits are sold either on an open market or by auction, the sale price for a credit is an estimate of its worth based on the current market valuation. This is where credit prices differ from the estimated costs of pollution. The cost for a company to produce more pollution than it has been allotted (e.g. the current price of a credit) is not necessarily related to the social cost of the pollution. There is a wide variation in valuation of the cost of one ton of NO_X and one ton of SO_2 (Table 4).

	Cost Per Ton of Pollution	
	NO_x	**SO_2**
	$1,658 [a]	$658 [a]
	$3,547 [a]	$4,682 [a]
	$2,588 [a]	$1,849 [a]
	$7,673 [a]	$13,166 [a]
	$1,060 [b]	$33,022 [c]
	$9,500 [b]	$2,595 [c]
	$18,869 [c]	$354 [c]
	$6,000 [d]	$2,571 [g]
	$2,500 [e]	$11,722 [g]
	$13,600 [f]	$3,829 [g]
		$4,568 [g]
		$220 [h]
Maximum	$18,869	$33,022
Average	$6,700	$6,603
Median	$4,774	$3,212
Minimum	$1,060	$220

[a] Perl et al. [16]
[b] Lave and MacLean [5]
[c] Funk and Rabl [17]
[d] Sholtz and Wochnick [18]
[e] NOx Credit [19]
[f] Carl Moyer [20]
[g] OAQPS [14]
[h] SO_2 Credit [21]

Table 4. Variation in cost estimates for NO_x and SO_2.

A study by Matthews and Lave (2000) [22] surveyed reports on the cost of emissions. This study also found that there is wide variation in the estimates for emissions costs (Table 5).

Estimated external costs ($/ton of air emissions)

Species	Number of studies	Min	Median	Mean	Max
CO	2	$1	$520	$520	$1,050
NO_x	9	$220	$1,060	$2,800	$9,500
SO_2	10	$770	$1,800	$2,000	$4,700
PM_{10}	12	$950	$2,800	$4,300	$16,200
VOC	5	$160	$1,400	$1,600	$4,400
CO_2 equiv.	4	$2	$14	$13	$23

Table 5. Variations in cost estimates for pollutants [23]

Duty Cycle Analysis

The data that are available from locomotive event recorders enables a complete estimate of the emission production. The event recorder data show how long each of the throttle positions was used. These data can then be converted into an estimate of the amount of emissions expelled [2] (Table 6). These values, when combined with the previously introduced cost per ton give an estimated cost per hour of operation.

Locomotive emissions per throttle setting				
Notch	**HC (g/hr)**	**CO (g/hr)**	**NO_x (g/hr)**	**PM (g/hr)**
Brake	1,400	1,849	1,335	622
Idle	478	492	309	228
Notch 1	226	361	1,299	131
Notch 2	192	464	3,000	140
Notch 3	361	1,197	7,267	427
Notch 4	294	2,772	14,014	336
Notch 5	595	3,895	25,584	348
Notch 6	748	5,872	33,600	499
Notch 7	826	3,302	39,766	585
Notch 8	984	3,034	47,027	697

Table 6. Locomotive pollutant production by throttle notch [2]

The social cost of running a locomotive for an hour at each throttle setting can be calculated (Table 7). Since this is an external cost, it does not include the cost of the fuel, the wear and tear on the locomotive, or the labor costs involved with running a locomotive.

Notch	HC ($/hr)	CO ($/hr)	NO_x ($/hr)	PM ($/hr)	Total
Brake	$2.16	$1.06	$1.56	$1.23	$6.01
Idle	$0.74	$0.28	$0.36	$0.45	$1.83
Notch 1	$0.35	$0.21	$1.52	$0.26	$2.33
Notch 2	$0.30	$0.27	$3.51	$0.28	$4.35
Notch 3	$0.56	$0.69	$8.49	$0.85	$10.58
Notch 4	$0.45	$1.59	$16.37	$0.67	$19.08
Notch 5	$0.92	$2.23	$29.89	$0.69	$33.73
Notch 6	$1.15	$3.37	$39.26	$0.99	$44.77
Notch 7	$1.27	$1.89	$46.46	$1.16	$50.79
Notch 8	$1.52	$1.74	$54.95	$1.38	$59.59

Table 7. Single locomotive pollution cost per hour.

Fuel Use Analysis

The cost of the pollution generated during the locomotive duty cycle is one way to quantify the social cost of locomotive use. Another approach is to analyze the pollution generated by burning a gallon of fuel. The USEPA has set a series of standards for the amount of pollution that a locomotive can produce [23]. The current standard known as Tier-2 applies to all locomotives built after 2004. Most new equipment is cleaner than these limits require (Table 8).

Estimated Tier-2 Emission Rates	
Pollutant	**lbs/gal**
NO_x	0.2271
PM	0.0079
HC	0.0119
CO	0.0586

Table 8. Estimated emission rates for line haul locomotives [23]

Reuse of dynamic brake energy by candidate trains on Cajon Pass has the potential to reduce annual fuel consumption by 525,000 gallons (Table 3) and pollution by about 80 tons (Table 9). Based on the total reduction, a social cost savings of almost $190,000 per year might be achieved. Together with the fuel savings, a total of $976,700 could be saved.

Pollution reduction based on fuel savings		
Pollutant	**Reduction (tons)**	**Cost Savings**
NOx	60	$168,000
PM	2	$8,600
HC	3	$4,800
CO	15	$7,800
Total	80	$189,200

Table 9. Locomotive emissions reduction and cost based on fuel savings.

Comparison of Analysis Results

To compare these two methods of environmental cost estimation, a sample train was used that consisted of six locomotives and 76 cars of mixed types. The event recorder data for this train's duty cycle were extracted (Table 10). Fuel consumption from TEM was 1,792 gallons, which translates (Table 8) to $645 in environmental costs. This is in comparison to the total estimated cost based on duty cycle (Table 10).

Notch	Time (hours)	Cost per hour	Total cost
Brake	2.2	$6.01	$79.60
Idle	1.6	$1.83	$17.64
1	0.3	$2.33	$4.06
2	0.3	$4.35	$9.02
3	0.3	$10.58	$18.74
4	0.2	$19.08	$27.03
5	0.2	$33.73	$45.65
6	0.3	$44.77	$70.07
7	0.1	$50.79	$34.11
8	0.6	$59.59	$220.58
		Total	$526.51

Table 10. Duty cycle and cost of emissions for sample train.

The similarity between these two values demonstrates that either method may be used to estimate the cost of pollution. The use of one method over the other should be dictated by the availability of the appropriate data.

5. CONCLUSION

The idea of reusing dynamic brake energy has been studied in various contexts for many years. Situations where it proves to be economically justifiable are difficult to find because of the specialized equipment and modifications that are required to capture and store this energy. However, fuel prices rise and environmental factors play a larger role in corporate decision-making, the feasibility of these types of projects also increases. Currently the fuel savings that are projected from energy recovery do not justify the required investment. However, the environmental costs associated with pollution could be enough to make a project such as this attractive.

The problem with using environmental costs as a basis for the financial feasibility of a project is that finding a definitive valuation for environmental impacts is difficult. The wide variation in available data shows that there is no one cost that can be agreed upon by all parties.

In order for environmental costs to be considered in the justification for implementing emissions reducing technologies, the railroad must receive compensation for the reduction. The current regulations on emissions credit trading do not allow trading between mobile and stationary sources. If the USEPA were to change this to allow railroads to trade credits, the value of the emissions reductions would be quantified for the railroads, thus allowing this income to be included in financial calculations. The Carl Moyer program [20] gives grants of up to $3,600 per ton of NOx reduction for the purchase of new equipment. This program is yet another way that railroads could quantify the value of emissions reductions.

Currently, the ways that railroads can receive a benefit from emissions reductions are limited. New programs and grants could help provide incentives for railroads to implement emissions reduction technologies. Increasingly stringent government regulations could also provide incentive by increasing the cost of producing emissions at the current level.

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