RECOVERING RAILROAD DIESEL-ELECTRIC LOCOMOTIVE DYNAMIC BRAKE ENERGY

BY

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ABSTRACT

RECOVERING RAILROAD DIESEL-ELECTRIC LOCOMOTIVE DYNAMIC BRAKE ENERGY

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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. If feasible, such as system could conserve fuel and reduce the environmental impact of railway operations. 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 an 81-mile route over 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 and possible pollution prevention benefits. First, there is an extended down grade longer than 25 miles, 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 900 kilowatt-hours per train. Assuming a 30% efficiency in the energy recovery system, as much as 20 gallons of diesel fuel could be saved per train. This equates to 680 gallons of fuel per day if all eligible trains made use of the technology, and a corresponding reduction in emissions. Larger amounts could be achieved if more energy recovery vehicles were used, up to an estimated maximum of 60% efficiency. Nevertheless, fuel savings do not provide sufficient economic incentive to warrant implementation of dynamic brake energy recovery at current fuel prices. Even when the environmental benefits are accounted for, a likely return on investment is about five years, which is greater than is typically acceptable for railroad capital investment projects.

To Julie

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CHAPTER 1: INTRODUCTION

Each year the Class 1 railroads use over 4.1 billion gallons of diesel fuel (Association of American Railroads 2005). This represents over 12% 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. Even 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 (Sierra Research and Caretto 2004). The amount and type of these pollutants can be partially controlled through locomotive diesel engine technology, but emissions 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 (United States Environmental Protection Agency 1998). 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 thesis examines the prospects for recovering and reusing energy from locomotive dynamic brakes. An 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 (Hay 1982) and is growing in popularity with the mass production of hybrid automobiles (Lave and MacLean 2002).

In the 1970's, the OPEC oil embargo and the resulting energy crisis increased awareness of the issue of fuel efficiency. This led to extensive research in the area of railroad energy efficiency. Although the impetus for such work abated in the 1980s, it was renewed again in the 1990s and 2000s, first because of interest in reducing emissions, and more recently as a result of sharp increases in petroleum prices.

1.1 Previous Research

In 1979, the Federal Railroad Administration (FRA) published two reports on modification of 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 where the infrastructure was available (Federal Railroad Administration 1979b). 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 (Federal Railroad Administration 1979a). In 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.

Together these studies showed 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 that was electrified or 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 has two characteristics that would make it suitable for a system that relied on dynamic brake use. It has long downgrades and a high density of train traffic. As such, this rail line would appear to have the greatest potential for demonstrating the technical and economic feasibility of an energy recovery system for United States railroad operations. Furthermore, because it is in a nonattainment area, the reduction in emissions associated with energy recovery would be particularly beneficial.

1.2 Cajon Pass

Cajon Pass is located on BNSF's southern transcontinental line between Barstow, CA and San Bernardino, CA, a total distance of 81 miles (Figure 1.1). It is comprised of approximately 25 miles of westward downgrade and 55 miles of eastward downgrade (Figure 1.2). Locomotives traveling this route are often 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 (1979a). 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, it might be feasible on trains that experience long periods of sustained dynamic braking such as Cajon Pass. An average of 81 trains per day pass over this line. The majority of these are intermodal with the remainder primarily mixed freight and unit trains.

There are major railroad yards at both San Bernardino and Barstow and these would serve as logical places for equipment change if such a system were implemented. Also, given the relatively short length of track covered, the capital expense of adding additional infrastructure would be limited and well defined.

Being located in the Los Angeles Basin means that air quality and air pollution are strictly regulated. This area has been designated a nonattainment area. Nonattainment areas do not meet the Environmental Protection Agency's standards for air pollution and must work toward reducing air pollution to meet these standards. Meeting these regulations requires financial expenditure as well as air quality and emissions monitoring. The current regulations can be expected to tighten in the foreseeable future. Reducing the total amount of locomotive emissions through the reuse of dynamic brake energy would help to meet these future regulations thereby reducing the cost of compliance.

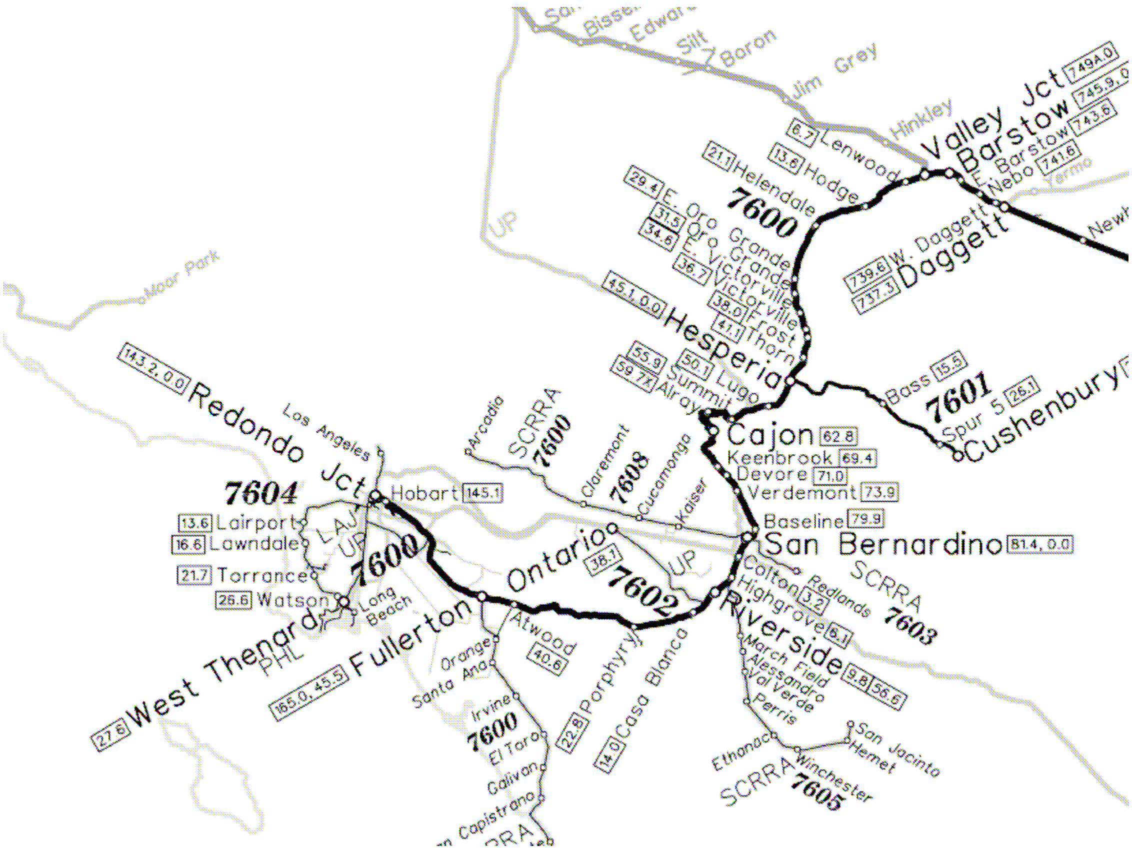


Figure 1.1 Map of BNSF’s Southern California lines

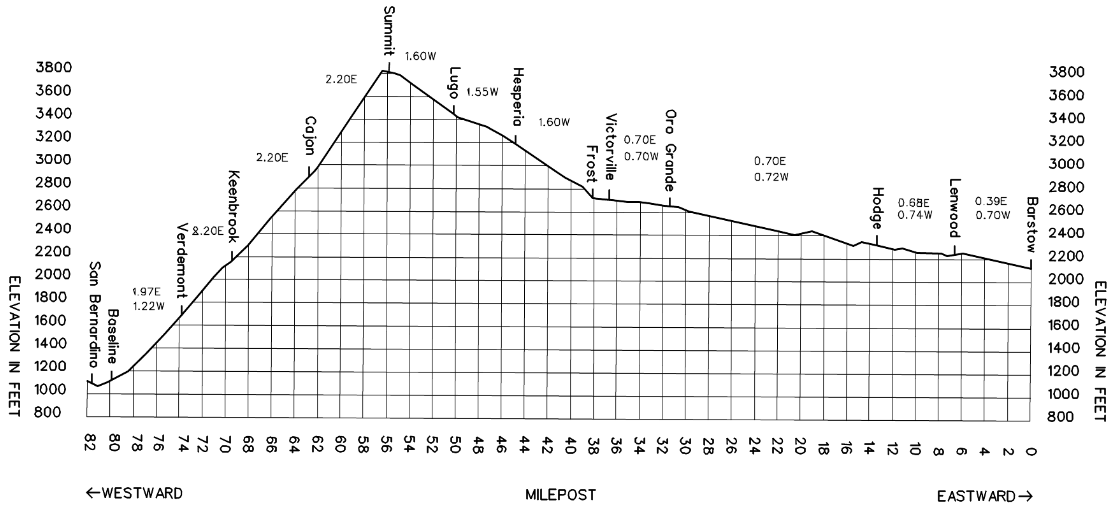


Figure 1.2 Grade chart for Cajon Pass

1.3 Scope of Study

In light of the previous studies related to locomotive dynamic brake energy recovery, this research focuses on the potential for recovery of this energy at a location where dynamic brake use is customary and where there is enough daily traffic to warrant an initial investigation. The conditions at Cajon Pass on the BNSF Railway were deemed suitable, so this section of track was chosen for this study.

The cost justification for the project will be analyzed based on two criteria. The first will be reduced fuel consumption, and the second will be reduced air pollution. Environmental benefits have not been considered in the previous studies. The level of these benefits is determined by the amount of energy that can be recovered based on dynamic brake use and railroad operations.

1.4 Summary of chapters

1.4.1 Chapter 1

Chapter 1 introduces the subject of the research, describes two previous studies demonstrated the technical feasibility of the concept, and introduces the idea of accounting for the environmental benefits as well as the economic savings from reduced fuel consumption. Also in this chapter is a description of Cajon Pass in southern California. This location was chosen for the study of energy recovery because of its long downgrades and high volume of traffic. Being located in southern California also means that reducing locomotive emissions is of particular importance. California has some of the most stringent air quality laws in the country and railroads are under considerable pressure to reduce emissions there.

1.4.2 Chapter 2

This chapter gives background information on locomotive dynamic brakes as well as three types of energy storage systems that would be feasible for use in conjunction with locomotive dynamic brakes. These two storage systems are: flywheels and batteries. The strengths and weaknesses of each type of storage system are discussed as well as the technology behind the way that they store energy.

1.4.3 Chapter 3

A train simulation program was tested to see if accurate figures for dynamic brake energy could be produced. AAR's Train Energy Model (TEM) was compared to actual locomotive event recorder data for trains operating on Cajon Pass. While some aspects of this program had been validated using data from actual trains, this was not the case for dynamic brakes. The dynamic brake energy portions of the simulation were found to be inconsistent when compared to the event recorder data. This eliminated the use of the TEM for simulating dynamic brake usage.

Not every train that travels over Cajon Pass would be applicable for energy recovery. The criteria for selecting applicable trains are defined, and an average number of trains to be considered is provided. The methodology for calculating dynamic braking energy using event recorder data is also described.

1.4.4 Chapter 4

Using locomotive event recorder data, an average value for the amount of energy consumed by the dynamic brakes was calculated. This value assumes 30% recovery and reuse efficiency. With this figure, appropriate reductions are made to the total available energy. The calculated energy was then converted into an estimate of fuel savings per train. The total fuel savings per year was calculated and shown as a cost reduction based on the decreased amount of fuel required to be purchased. A preliminary estimate of the cost of an energy storage vehicle is also developed for use in the cost benefit analysis.

1.4.5 Chapter 5

A social cost can be applied to pollution. The exact value for this cost can be difficult to set. A number of studies have been conducted to try and rationally define the cost to the population as a whole for various types of air pollution. These numbers as well as the price of the pollutants on the emissions trading market were collected and summarized. The amount of each main pollutant found in locomotive emissions was also researched. These two data sets were combined to produce an estimate for the social cost of running a locomotive. Social benefits were calculated using the reduction in emissions based on reduced fuel consumption.

1.4.6 Chapter 6

The costs and benefits developed in earlier chapters are combined, and the level of investment that is justified on the basis of the estimated savings is determined. Savings from both reduced fuel consumption and emissions are accounted for, and a return on investment of approximately five years is calculated. A sensitivity analysis of the effect of fuel price on the estimated rate of return is also conducted.

1.4.7 Chapter 7

A brief summary of the conclusions is presented and areas for future study introduced.

CHAPTER 2: BACKGROUND

2.1 Dynamic Brakes

2.1.1 Introduction

Dynamic brakes play an important role in the control of North American train operations. Because of their prevalence, it is important to understand how they work and the advantages and disadvantages of their use. Dynamic brakes are not limited to use in locomotives. They are used in hybrid automobiles, industrial machines, and some elevators, which all share two main characteristics, the use of electric motors and the need for a way to slow rotating machinery with little wear.

2.1.2 Dynamic Brake description

Electric and diesel-electric locomotives use electric traction motors attached to the axles to apply tractive force to the wheels. An electric motor can act as a generator when a magnetic field is present and a rotational force is applied to the rotor. During dynamic braking, the rotors of the electric motors are allowed to rotate and produce electricity. By generating electricity, the conversion of energy provides resistance to movement that reduces the speed of the train. The converted electrical energy is then used or expelled into the atmosphere as heat.

Dynamic braking is a general term used to describe the use of an electric motor as a generator to dissipate energy. This type of braking is more precisely described by one of two terms, *regenerative* and *rheostatic* braking (Judy and Johansson 1954). The difference between the two types of dynamic braking is what is done with the electricity after it has been produced. In regenerative braking, the electricity is either immediately reused by other locomotives, or it is stored for later use. This electricity can either be transmitted through overhead catenary wires or an electrified third rail, as is the case with electric locomotives, or it can be stored onboard through the use of a flywheel, battery or other energy storage system (Judy and Johansson 1954). Rheostatic braking occurs when the electrical energy that is produced is run through resistors and dissipated as heat energy. A rheostat is a device that regulates the current flowing through it by changing the resistance. For the case of rheostatic braking, this resistance provides a force against which work may be done. While regenerative braking leads to a more efficient system because of the reuse of energy, the infrastructure that is required for this type of braking is not always available. Diesel-electric locomotives run primarily on track that has not been electrified. For this reason, rheostatic dynamic braking is what is used on diesel-electric locomotives.

Ultimately dynamic braking is based on the First Law of Thermodynamics. Translational energy in the form of train movement is converted into electrical energy. The quantity of energy that has been converted is directly reduced from the total translational energy of the locomotive (or train). This reduction in energy reduces the speed of the train through the equation:

$$KE = \frac{1}{2}mv^2$$

where: KE = kinetic energy

m = mass

v = speed (velocity)

The amount of energy reduction required to slow a moving train is large. A 5,000-ton train reducing its speed from 30 mph to 25 mph requires that 124,640 kJ (34.6 kWh) of energy be dissipated through the dynamic brake, the air brakes, or a combination of the two.

2.1.3 Dynamic Brake Use

2.1.3.1 Air Brakes

With air brakes, force from an air cylinder is applied via a series of rods and levers to the brake shoes that press against the wheels or special axle-mounted brake disks. The resulting friction provides resistance that slows the train. This frictional force converts the rotational energy of the wheel directly into heat energy.

Because the brake pads or shoes must come into contact with the wheel (and brake disk for most passenger equipment), both the shoes and the wheel (or disk) experience wear and thus eventually need to be replaced. Brake shoes are cheaper and easier to replace, so they are designed to wear faster than the wheels. Brake shoes are made of either iron or a composite material. The material of the brake shoes is softer than the hardened steel of the wheels (Andrews 1986). This reduces the frequency of wheel replacement but increases the frequency of shoe replacement. Wear to both wheels and shoes costs money due to the material cost of replacing components and the opportunity cost while equipment is out of service for repair.

Wheels and brake disks have a thermal capacity (Air Brake Association 1972). As heat builds up, the material of the brakes softens and the efficiency of braking is reduced. Consequently, more force must be applied to the shoes to provide the same level of braking. In circumstances in which extended heavy braking is required, the rate of heat build up may exceed the rate of heat loss to such an extent as to cause overheating. The immediate effect is a loss of braking efficiency or "brake fade." This heating can induce thermal stresses in the wheel or disk that can damage them, thus increasing the likelihood of fatigue failure.

In the single line air brake systems commonly used in North American freight service, the system of air lines, reservoirs, and compressors introduces a limiting rate at which the pressure in each car's individual reservoir can be restored. Each change in braking force involves a corresponding decrease in the air pressure inside the reservoir. A series of adjustments to the braking force in quick succession can deplete the pressure in the reservoir and render the brakes inoperable until enough time has passed for the pressure to be restored.

With standard pneumatic brakes, it is possible to apply so much pressure to the brake shoes that the wheels lock up and stop rolling. This is harmful to both the rail and the wheels. Wheels in this situation will wear and form flat spots that greatly increase the dynamic loads applied to the rail once they start rolling again (Armstrong 2000).

Passenger cars use more specialized equipment than freight cars because of the limited number and variety of cars and the greater imperative for safety and passenger comfort. Consequently, the air brake systems on passenger equipment are more flexible. Most passenger trains have brake systems that allow for continuously variable control of the braking force being exerted (Air Brake Association 1972). These systems may use two separate brake pipes so that brake control and reservoir recharge are separated or may use electrically controlled pneumatic brakes. Locomotives have a separate braking system, the independent brake, which only applies the brakes on the locomotive. This independent brake also allows for graduated release pressure. In this respect, the performance of these air brake systems is more like that of dynamic brakes.

2.1.3.2 Dynamic Brake Advantages

The main advantage that dynamic brakes possess is that they do not use mechanical friction. This differs from pneumatic brakes as described above. Since dynamic brakes do not rely on mechanical friction, their use does not cause wear on the wheels of the locomotives or cars (Armstrong 2000).

The second advantage of dynamic brakes is that they allow for greater control of the braking characteristics of the train. With the single pipe air brake systems that are standard on most North American freight trains, once a brake application is made, gradual release is not possible. Once a brake application has been made, the only reduction that is possible is a complete release. With dynamic brakes, the applied braking force is almost completely variable between no braking and full braking. This substantially increases the amount of control that an engineer has over the train (Air Brake Association 1972), and this also leads to reduced wear on the draft gear and rail (Hay 1982).

Unlike air brakes, dynamic brakes are not subject to brake fade, so there is no time limit on their use. As such, they are particularly useful on long down grades where braking applications may last an hour or more. The advantages of using dynamic brakes on grades are further increased when helper locomotives are used. Helper locomotives are used to help move trains up long grades. The added dynamic braking force that helpers provide on the downgrade means better control of the train is possible and less air braking is required. A train must be able to stop itself through a full service brake application without relying on dynamic brakes or emergency braking. However, reducing the reliance on air brakes allows for a greater margin of safety by assuring that there is a reserve of available braking force that can be applied if the situation calls for it. In short, use of helper locomotives enables heavy trains to be pulled up long grades more effectively and to be more safely controlled on the way down (Armstrong 2000).

Another advantage of dynamic braking is that wheel slide due to excessive braking force cannot occur. Dynamic brakes only produce a retarding force when the wheels are rolling, and this force reduces as the rotational speed approaches zero. The wheel will be providing less and less braking force as its rotation slow and zero braking force when it stops turning all together, effectively eliminating slide due to excess braking force (Armstrong 2000). This system enables maximum braking force to be applied without worrying about damaging rails or wheels due to sliding.

2.1.3.3 Dynamic Brake Disadvantages

Dynamic brakes have three drawbacks that must be accounted for to provide safe and reliable operation. Because they are inherent in the system, they will not be eliminated until a new way of providing braking is developed that is both robust and cost effective enough to replace the current technology.

2.1.3.3.1 Dynamic Braking Limited to Locomotives

Dynamic braking force is necessarily located only on the locomotives. Because of this, only a limited number of axles are available to provide braking. This factor combined with the maximum coefficient of friction sets an upper limit to the total amount of braking force available. This is less than the braking force that can be applied with the air brakes acting on every car in the train. It also changes the way that trains must be handled. The concentration of braking force at the locomotives necessitates a gradual application in order to prevent severe slack run-ins (Air Brake Association 1972). Dynamic brakes share this drawback with the independent brake on locomotives.

Dynamic brakes typically are set up to have eight “notches” like their throttle counterparts. Because dynamic brakes are continuously variable, these notches are necessary to provide consistent feedback for the engineer. The positions provide a reference point for the locomotive engineer so that when a specific level of braking is required he or she will know exactly which setting is needed.

2.1.3.3.2 Fuel Consumption

Dynamic brake operation consumes fuel. In order for dynamic brakes to function, there must be current to the electromagnet in the traction motor. The main generator, which is powered by the diesel engine, supplies this power, and consumes fuel in the process (DB-1 and DB-4 in Table 2.1). Thus the benefits to train handling and reduced wheel and brake wear attributable to dynamic brakes must outweigh the additional fuel cost due to their use.

Throttle Notch	Fuel Consumption (Gal/hr)	Locomotive Power (hp)	Efficiency (hp-hr/gal)
8	184.7	3808	20.6
7	157.5	3324	21.1
6	123.2	2530	20.5
5	86.9	1749	20.1
4	64.9	1298	20.0
3	47.8	943	19.7
2	22.8	418	18.3
1	12.0	189	15.8
Idle	3.1	0	0.0
DB-1	4.4	--	--
DB-4	14.5	--	--

Table 2.1 Typical Fuel Consumption Rate,
Horsepower and Efficiency of an EMD SD60 Locomotive (Rhine 1996)

In the example presented here, when the locomotive is producing half of its full dynamic braking force (DB-4), it is consuming slightly more fuel than when it is in the first throttle position (Table 2.1). When the dynamic brake is in its lowest setting, it is using more fuel than when the engine is simply idling. (Table 2.1 is incomplete with respect the fuel consumption while in dynamic braking mode. Of the eight available braking notches, data are only given for two settings.)

2.1.3.3.3 Dynamic Brakes Cannot Stop a Train

As discussed above, the wheels must be moving in order for dynamic braking force to be developed. The current that is generated from the traction motors decreases as the wheels rotate more slowly. Dynamic brakes are not able to completely stop a train. They are used in the situations where the train is moving and needs to slow down but not stop. For long descents and minor speed adjustments, dynamic brakes are advantageous. For emergency or regular stopping and quick decelerations, air brakes provide better performance.

2.1.4 History of Dynamic Brakes

The history of dynamic brakes in locomotives is closely related to the history of electric traction motors in locomotives. Even before steam locomotives had reached the height of their efficiency or ubiquity, electric locomotives were being used in situations where electric motors excelled and steam locomotives were either unable or unfeasible to be run. These cases included areas where steep grades are encountered or where heavy loads were to be hauled. This was due to electric traction's higher adhesion levels when compared to steam (Bezilla 1980).

The early use of electric locomotives was commonly in mountainous terrain or mines (Haut 1969). These were locations where the added infrastructure cost was justified by the savings in operating cost. During this era, electrical distribution was not very widespread. There were no power generating plants available to provide electricity, so each electrical installation had to have its own power plant. Also during the early stages of electrification, there was not a clear consensus regarding whether AC or DC power was better (Bezilla 1980).

The earliest prototype locomotives were built in the mid 1800s (Haut 1969). These electric vehicles were primitive, inefficient, and bulky. The electricity used to power them was supplied by batteries. This was the state-of-the-art way of generating electricity for vehicles at the time. Not only was the technology for generation of electricity inadequate, but electric motor technology was also of limited value for industrial purposes (Middleton 2001). Electric motors were not powerful enough to take the place of large steam engines.

The motors of early locomotives consisted of iron bars attached to the axles of locomotives. Electromagnets were then used to pull these bars around, thus turning the axles and attached wheels (Haut 1969). While this is roughly similar to the design of modern electric motors, it was primitive and inefficient. The design of the propulsion system effectively set an upper limit as to how fast the vehicle could move or how much tractive effort could be produced.

The first practical electric locomotive was built by Robert Davidson in 1842 (Haut 1969). This locomotive had two axles and weighed seven tons. It could move a load of six tons at a speed of four miles per hour but other than that, little is known about it. After the development of this locomotive was discontinued, there was little further progress in locomotives until about 1880. By that time, electrical technology had advanced enough for large currents and voltages to be reliably produced. This made it possible to create enough power to move a larger mass than had previously been possible (Haut 1969).

The first use of dynamic braking was on a short experimental line in Switzerland (Haut 1969). Its sole purpose was to connect a hotel with a town several hundred feet down a mountain slope below it. The vehicle on this rack railway could accommodate four passengers at a time, and on the trip down the mountain it used its motor as a generator to provide braking force.

2.1.5 Contemporary Dynamic Brakes

2.1.5.1 Standard Dynamic Brakes

Although dynamic brakes have been used since the early days of electric locomotives, their widespread use did not occur in diesel-electrics until recently. The type of dynamic braking used on diesel-electric locomotives is rheostatic braking. Current freight locomotives do not have any means for storing the energy onboard and do not use catenary or third rail required for regenerative braking.

Electric locomotives more commonly power passenger trains than freight trains, particularly in North America. With electric locomotives, electricity generated during dynamic braking is transferred to the catenary or third rail. This power can be used by other trains currently running on the line or stored by wayside facilities. These facilities typically employ large flywheel systems to store the energy (Tarrant 2004).

The system used for dissipating the energy produced during dynamic braking is specially designed to handle large amounts of energy. The current produced by the traction motors passes through a series of resistors that convert the electrical energy into heat. The resistance of this resistor grid is low, less than one ohm, so that a situation close to a dead short occurs. This situation allows for the most energy to be dissipated (Runion 2005).

The high amperage and voltage characteristic of dynamic brake resistance grids (700+ amps and 600 volts) create a large amount of heat (State of California 1999). Part of the value of dynamic brakes is that they can be used for extended periods, but in order to do so, this heat must be dissipated rapidly enough to not damage the resistor grids. This is accomplished by large fans that force cooling air through the grids, which are designed to maximize heat transfer. If the fans become inoperable or the ducts clog with dirt and debris, the heat buildup and the arcing that occurs within the grids can cause them to explode and throw shrapnel and molten metal yards away (State of California

1999). The resistor grid fans are powered by the electricity generated by the traction motors during dynamic braking. This is beneficial for two reasons.

First, this can be thought of as free power. The electricity produced by dynamic braking has already served its purpose as a force to slow the train. The electricity that the fans use is energy that would not be used for any other purpose. Second, the system is self-regulating. As the power flowing through the resistor grid increases, so does the speed of the fan. This insures that as heat production increases, so does the flow rate of air through the grid (Judy and Johansson 1954).

Figure 2.1 shows the ductwork and fans in an example dynamic brake resistor grid, and Figure 2.2 shows a typical resistor grid. The grid is designed as a heat transfer device. To accomplish this, its surface area must be maximized while maintaining adequate airflow.

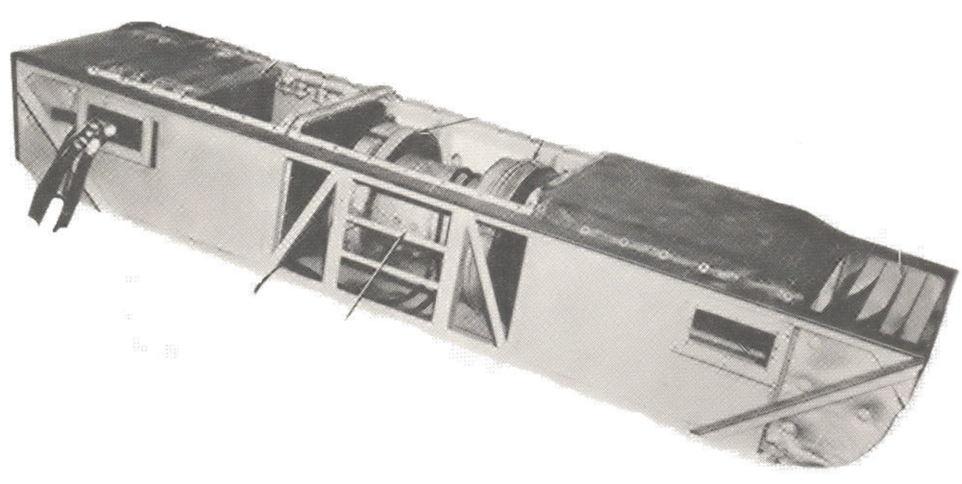


Figure 2.1 Example of the resistor grid ductwork (Judy and Johansson 1954)

Figure 2.2 Typical resistor grid (Judy and Johansson 1954)

The controls on a dynamic brake are simple from the locomotive engineer's point of view. All he or she sees is the position that the dynamic brake lever is in and an ammeter that shows the amount of current being produced by the traction motors. The ammeter is important because high current levels could cause damage to the traction motors, resistor grids, and wiring (Air Brake Association 1972). The maximum current allowed is given as 700 amps. The regulation of this current was once the job of the locomotive engineer, but it is now is regulated by automatic controls within the locomotive. The regulation of dynamic braking current is the most important factor in protecting the electrical system of the locomotive.

At high currents, arcing may occur within the traction motors and electrical connections, and the braking grids could overheat and melt. These three failures are avoided by limiting the amount of current produced during braking (Judy and Johansson 1954).

The importance of the traction motors, resistor grid, and blower in the dynamic brake system has already been discussed. For the traction motors to work as generators, an electromagnetic field needs to be present in the motor. Running the diesel engine and main generator creates this field. The electrical current produced from these components is then fed through a special set of windings in the motor. This set of windings creates the necessary electromagnetic field in the motor, and allows for control of the amount of power being produced by the traction motors. This is what consumes the additional fuel.

2.1.5.2 Extended Range Dynamic Brakes

Extended range dynamic brakes are a special type of dynamic baking system that has been modified to increase the speed range at which an effective amount of braking force is applied. In standard dynamic brakes, the lower limit to their usable speed range is about 20 mph. At this speed, the maximum braking effort is produced, but below this speed, the braking force drops off almost linearly to zero pounds of force at zero mph. At 10 mph, only half of the maximum amount of braking force is available (Figure 2.3).

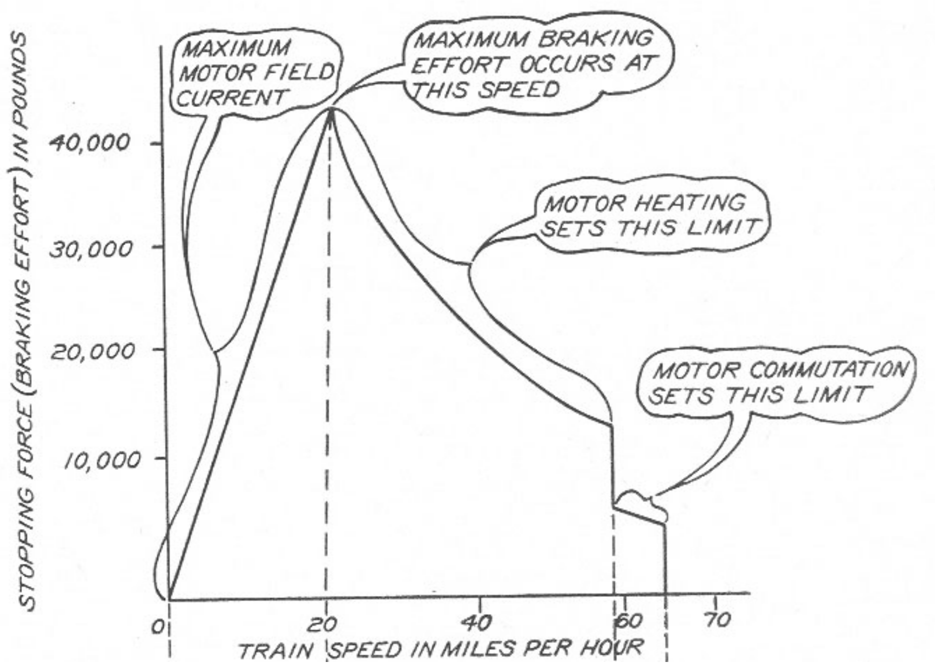


Figure 2.3 Change in braking force with speed for standard dynamic brakes (Judy and Johansson 1954)

The braking force diagram changes greatly with extended range dynamic brakes. Maximum braking force is available down to about 5 mph (Figure 2.4). Below this speed, the force drops off linearly to zero, as with standard dynamic brakes.

The change from standard to extended range dynamic brake behavior is accomplished as follows. A portion of the resistor grid is shorted out by switch gear. This causes a drop in the resistance across the grid. A drop in the resistance changes the electrical characteristics of the circuit and allows more current to flow (Air Brake Association 1972).

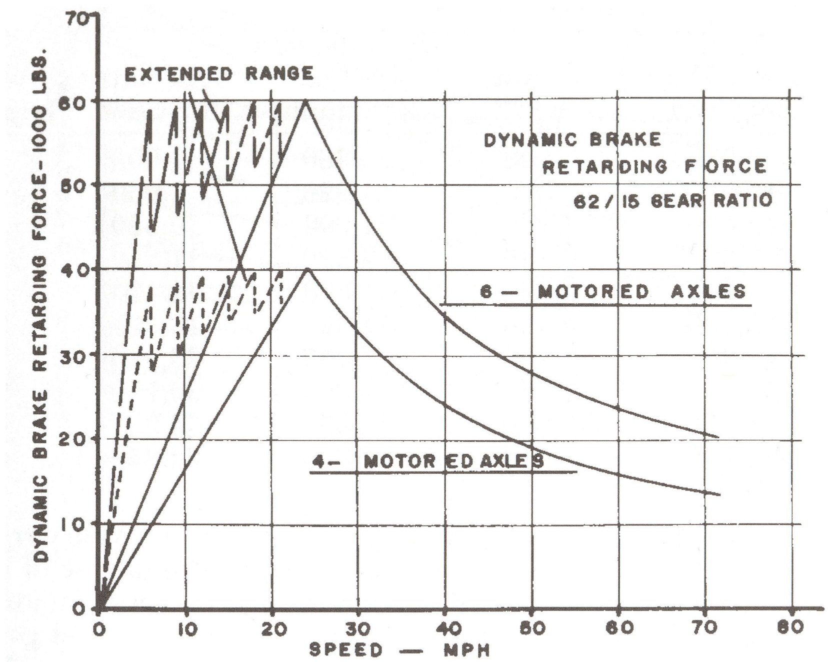


Figure 2.4 Comparison of extended and standard dynamic braking charts (Air Brake Association 2004)

Ohm's law states that the voltage, V, across an element in a circuit is the product of the current, I, passing through the element and the internal resistance, R, of the element:

$$V = I * R$$

This is valid for the resistor grid in locomotives as well. The grids have a constant resistance or a resistance that can be changed, as is the case with extended range brakes. As noted above, this ability to change resistance is what allows extended range dynamic brakes to work at lower speeds.

Also from basic electrical theory, the equation for power, *P*, dissipated across a circuit element can be written in two ways. The first equation shows its basic form, and the second equation is when Ohm's law is used for substitutions.

$$P = I * V$$

$$P = I^2 * R$$

Using the equation above, if the resistance stays constant and the maximum current allowed in the circuit is 700 amps, then the maximum braking power is constant. This is when the maximum braking effort is produced. The maximum braking effort is not constant because the voltage produced by the traction motors is not constant. This voltage increases with speed. That means that at around 20 mph the optimal voltage is being produced, and as the train speed decreases from 20 mph, a lower voltage is produced.

As the voltage from the traction motors decreases, so does the current because the resistance is staying constant. This decrease in current then reduces the amount of braking power that is being produced. To counteract this, once the speed (and corresponding voltage) reaches a certain threshold level, a portion of the resistor grid is shorted out, and the resistance is lowered. Returning to the equations shows that with this new, lower resistance, the current is increased even though the voltage has dropped. Braking power is increased because the current has a much greater effect on the power dissipated than the resistance does. This is why reducing the resistance of the circuit enables more power to be dissipated then would normally be possible.

Similar to how dynamic braking force decreases as wheel speed decreases, a decrease in braking force is seen as wheel speed increases past about 20 mph (Figure 2.4). The phenomenon in this region is explained by the functional relationship between wheel rotational speed and voltage. The higher voltage produced by the traction motors as they spin faster causes the current through the breaking grids to increase. This current continues to increase until the maximum safe limit is reached. At this point, the current must be limited in order to protect the equipment. This reduction in current directly affects the amount of power being dissipated through the resistor grids and thus the braking effort (Judy and Johansson 1954).

2.1.6 Types of Electric Motors

There are two types of rotational electric motors: alternating current (AC) and direct current (DC) signifying the nature of the electric current used. Although the basic principals of their operation are the same, there are several important differences in the basic design of AC and DC motors.

An electric motor has two main parts, the stator and the rotor. The stator is the part of the motor that is static, and the rotor is the rotating shaft and its various attachments.

The rotation of an electric motor is produced by the crossing of magnetic flux lines inside the motor. The magnetic field created in the stator interferes with the magnetic field created in the rotor. Since the rotor is the only part that is free to move, it moves when the force created from the meeting of these two fields is greater than the resistance on the shaft of the motor. The differences between AC and DC motors come about from the way in which the two opposing fields are created. These differences are explained below.

2.1.6.1 AC Motors

Electric motors that are powered by alternating current are called AC or induction motors. The term *induction* comes from the way in which the rotating motion is produced. In induction motors, the electric current in the rotor that produces the electromagnetic field is not directly provided. This current is produced through induction (Gourishankar and Kelly 1973).

Since the electric current in the rotor is induced, no electrical connections to the rotating shaft must be made. This eliminates the arcing that normal occurs with these type of connections. It is for this reason that AC motors can be run at low speeds and high torques without causing damage to themselves (Gourishankar and Kelly 1973).

2.1.6.2 DC motors

The direct current power source for DC motors necessitates an applied electric current to the commutator windings in the rotor. This current is introduced to the rotor by brushes typically made of carbon. The current creates a magnetic field that works against the field produced in the stator. As the rotor turns, the brushes are continually energizing new sets of windings. This creates the rotational force that causes the rotor to continue turning.

On disadvantage is that each time a brush makes the transition from one set of windings to another, an arc occurs. These arcs can damage both the brush and the rotor. During periods of high current draw, such as low speed, high torque movement, these arcs are the largest and most damaging. It is for this reason that DC motors have a minimum safe operational speed (Gourishankar and Kelly 1973).

2.2 Flywheels

Use of flywheels as a means of energy storage predates the use of the wheel for transportation (Genta 1985). The earliest use of flywheels dates to tools used around 3,000 B.C. The tools that incorporated flywheels at that time included primitive drills and spindle whorls. For each tool, the energy stored in the flywheel came directly from the user's movements. The benefit of using a flywheel was that once the tool was set spinning, the user could then concentrate on the task at hand without needing to worry about keeping the tool moving. The flywheel would continue to spin until all of the stored energy was used. The duration of the rotation depended on the size of the flywheel and its initial energy. The energy was not meant to be stored or used over long periods of time, so the duration of unassisted spinning was on the order of seconds, rather than minutes, hours and days as is possible with modern flywheel technology. These simple flywheels were made from available materials that included stone, clay, and wood (Genta 1985).

Later developments in flywheel technology enabled large flywheels such as those used in steam engines. Because steam engines typically had only one or two cylinders, their motion varied depending on where the piston was in its stroke. The flywheel smoothed the motion of the engine so that a more consistent speed could be obtained. These flywheels were run at relatively low rotational speeds and used low strength materials such as cast iron and lead (Genta 1985). These materials had a high density that made them more space efficient than earlier wooden counterparts. The higher density increased the amount of kinetic energy that could be stored in the same space.

2.2.1 Stored Energy

The amount of energy that can be stored in a flywheel is described by the following equation:

$$E = \frac{1}{2} I \omega^2$$

where: E = stored energy,

I = moment of inertia,

ω = angular velocity.

Two things affect the total energy stored in a flywheel, the inertia and angular velocity of the flywheel. As each of these properties increase, so does the energy stored in the flywheel. The increase in stored energy is linear with respect to inertial increases, and it increases with the square of angular velocity.

To increase the moment of inertia of a flywheel, two things can be done. First, the shape of the flywheel can be changed while keeping the total mass the same. Moving mass farther away from the center of rotation by either creating a disk that is thicker toward the outer edge and thinner at the hub or by using spokes supporting an outer rim both serve to increase the moment of inertia while maintaining the same total mass.

The second way of increasing the moment of inertia of a flywheel is to increase its mass. This can be accomplished by either using a material with a greater density, thus increasing the moment of inertia while keeping the shape and size the same, or by keeping the same material and adding more of it, thus increasing both mass and size. Both of these methods are effective when the flywheel experiences low rotational speeds that do not introduce high stresses. The increase in the moment of inertia affects the stored energy linearly i.e. the amount of energy storage increases proportionally with the increase in the moment of inertia. In this way, total energy storage must be balanced with the size of the flywheel.

The second way that the stored energy can be increased is by increasing the angular velocity at which the flywheel is spun. From the previous formula, stored energy increases with the square of angular velocity. This makes increasing the angular velocity of the flywheel beneficial because it yields benefits that increase much faster than with increasing the moment of inertia. Current research is focused in this area because of the weight savings that can be realized by increasing angular velocity instead of moment of inertia (Tarrant 1999).

The problem with increasing the angular velocity of a flywheel is that as rotational speed increases, the stresses produced within the flywheel also increase. At high rotational speeds, a low strength flywheel can fail and shatter. Upon failure, all of the stored energy is transferred to the broken pieces of the flywheel and become shrapnel that poses a safety hazard to nearby personnel and equipment. Therefore, high-speed flywheels must be made out of materials with high tensile strength and housed in heavy-duty enclosures that can prevent shrapnel from escaping the housing in the event of a failure. Common high-speed flywheel materials include Kevlar and carbon fiber composites (Genta 1985). The centrifugal force on the outer edges of a spinning rim-type object is given by the equation:

$$F = 2\pi * \rho\Delta r * r^2 * \varpi^2$$

where: ρ = density

Δr = thickness of rim

h = height of rim

ω = rotational velocity

r = radius

The stress experienced by the material in the rotating rim is this force divided by the area of the rim. This stress is:

$$\sigma = \rho\Delta r * \omega^2 * r$$

where: σ = stress

When this stress exceeds the yield strength of the material used for the flywheel, deformations in its shape will occur. Depending on the design of the flywheel and its housing, these deformations may be large enough to cause contact between the flywheel and the housing. Although this is considered a safe failure mode in that there is no violent release of energy, the flywheel system becomes unable to perform its function and must be replaced.

For materials that have a very high strength and low ductility, there is no yield point. These materials will fail in a brittle and explosive fashion. When the stress in the flywheel reaches the ultimate strength of these materials, sudden and violent failure occurs. Due to the variability of flywheel manufacture, the calculated stress in a production flywheel is never allowed to reach this level. Flywheels are only allowed to spin at about 40% of their maximum design speed in order to provide a margin of safety (Genta 1985).

2.2.2 Flywheel Types

There are many designs of flywheels. With all of the available variations, the specific needs of the proposed application must be taken into account. Flywheel materials are either isotropic or composite in composition. The main variations in shape are listed in Table 2.2.

Radial
Rim-type
Pure circumferential wound
Radial-wrapped core
Pseudo-isotropic disk (e.g. laminations)
Geodesic wound
Rods or bars
Concentric rings

Table 2.2 Flywheel types

The differences between the designs are their ease of manufacture and final shape. Each shape has its own advantages and disadvantages that can compliment the properties of the material used and the energy storage requirements. These properties can include strength, ductility, allowed modes of failure, total energy stored, duty cycle, and weight limits among others (Energy Research and Development Administration 1975).

Apart from the technological challenges involved with building a high energy density and efficient flywheel, the system of storing and extracting that energy must also be efficient. There must be little loss in the energy storage or extraction process. Also, a means of monitoring the amount of energy stored is needed. Forcing the system to store more energy than it is designed for may damage the flywheel and shorten its life or even cause failure as described above.

As stated previously, energy stored in a flywheel is dependent on two things: rotational speed and inertia. Of these, speed is the most common way of changing the stored energy of a flywheel. Speed changes are safe as long as the flywheel material is strong enough to withstand the induced stresses. When the speed of a flywheel cannot be increased, its inertia must be increased. Changing the inertia of a rotating flywheel is a difficult task. The previously described methods for changing the inertia of a flywheel are complicated when the flywheel is in motion. Flywheels with this capability are called variable inertia flywheels. They have been created and tested in laboratories, but the benefits gained from their variable inertia do not justify the added expense and complication (Genta 1985).

In the laboratory prototypes, a change in inertia has been produced by either pumping a liquid into and out of a hollow flywheel (change in mass) or through the use of flexible wires that bend outward (mass moves away from the center) (Genta 1985). These devices exhibit lower energy densities than their fixed inertia counterparts because of the space required to allow movement of the components.

In fixed inertia flywheels where stored energy is directly related to rotational speed, rotation slows as energy is dissipated from the system. This can cause problems for applications that require constant rotational speeds to work efficiently. For short burst type applications, the change in rotational speed may be small enough that its effects are manageable. The applications that require longer sustained discharges could include mechanical drives and generators. Each of these applications has a speed at which their efficiency is the highest. The use of a directly connected flywheel would mean that the system can only run at greatest efficiency once during the discharge cycle. To insure that the devices that are using the flywheel's energy are running efficiently, continuously variable transmissions (CVT) are used (Energy Research and Development Administration 1975).

2.2.3 Continuously Variable Transmissions (CVT)

The purpose of a CVT is to provide a constant rotational speed output that is independent of input speed. Because of the variable nature inherent in their design, it is difficult to build an efficient CVT. While standard gear transmissions themselves have a very high efficiency, CVT's usually suffer from low efficiencies. The most common types of CVT's use pulleys to produce the large number of gear ratios required. While pulley systems are the most common and oldest types of CVT's, they are not the only types. Electrical systems employing a motor-generator are also used as well as systems that use hydraulic pumps. As is typically the case, the more components that are in a system, the lower its efficiency.

Although flywheels by themselves can be very efficient, the requirements of the output that they drive can reduce the total flywheel system efficiency. For flywheel applications where CVT's are not required, the efficiencies can be very high. In these applications, the flywheel is used for smoothing variations in mechanical output. When the output is required to be electrical, the high efficiencies seen in electrical motors and generators (90%-95%) help to keep the total efficiency of the system high (Genta 1985).

2.2.4 Bearings

A bearing supports the rotating shaft of the flywheel. The common types of bearings used are rolling element, hydraulic, and magnetic suspension (Energy Research and Development Administration 1975).

2.2.4.1 Rolling Element Bearings

Rolling element bearings are the most common type of bearings used. Even with advances in metallurgy and lubrication, these bearings suffer from failure due to the wear placed on them from direct contact of the shaft and supports. The direct contact inherent in these types of bearings also limits the maximum rotational speed of the shaft they support. In most high speed flywheel applications the flywheel and thus the bearing must be located within a complete or partial vacuum to reduce aerodynamic drag losses. Mechanical bearings such as these are valuable for the simple reason that they can be used in vacuums. Lubricants with a low vapor pressure can be used in partial vacuums without concerns about evaporation.

Rolling element bearings may be a backup system when used in conjunction with other more advanced bearings. Rolling element bearings work without any external control system (Genta 1985). They can be used as a failsafe mechanism in situations where power to the advanced bearing system is lost.

2.2.4.2 Hydraulic Bearings

Hydraulic bearings can either be hydrostatic, hydrodynamic, or fluid film. The main way in which these bearings differ from rolling element bearings is that the rotating load is supported purely by the fluid rather than by the solid rolling element. The use of a supporting fluid reduces the mechanical friction of the system, therefore indefinitely extending the life of the bearing. The only mechanical parts subject to wear are in the fluid control system and seals since there is no direct contact between the rolling element and the supports.

Fluid bearings are not as easily adaptable to operation in a complete or partial vacuum inside the flywheel system. The vacuum requirement limits the number of available lubrication fluids. While some fluids can exist in vacuums as low as 1-micron ($1.45x10^{-5}$ PSI), most common fluids have a vapor pressure much higher than this (Energy Research and Development Administration 1975).

2.2.4.3 Magnetically Levitated Bearings

The third type of bearings are magnetically levitated. These bearings rely on the attractive or repulsive forces produced when two magnetic fields come within close proximity of each other. These magnetic fields can be produced either by permanent magnets or electromagnets. Bearings of this type show the greatest prospects for providing support with very low drag. The flywheel is completely suspended by the magnetic field without coming into physical contact with the surrounding supports; therefore, the only friction involved is the aerodynamic drag associated with the rotating flywheel. In a complete or partial vacuum system, this drag is all but eliminated. These bearings typically employ rolling element bearings as a backup in case there is a loss of the magnetic field or if the flywheel experiences strong dynamic forces (Genta 1985).

Flywheel energy storage systems are most efficient when their input and output are mechanical. Each conversion of energy reduces the total amount of energy available because of inefficiency inherent in the conversion process. Flywheels themselves are an efficient form of energy storage, but when the energy costs of the required atmospheric and storage control systems are taken into account, total system efficiency is reduced and these factors must be accounted for in assessing their potential.

2.3 Batteries

The energy stored in flywheels is in the form of mechanical energy, whereas batteries provide storage in the form of chemical energy. The chemical reactions that occur in a battery require the movement of electrons. This electron flow is regulated so that a path is only available when the terminals of the battery are connected. The chemical reaction then takes place only when the battery is connected to a circuit.

2.3.1 Battery Types

There are two types of batteries: primary and secondary. Primary batteries rely on an irreversible chemical reaction. Once their charge is depleted, only a small percentage of the original power can be replaced. They must be discarded and replaced with new batteries. Primary batteries are often cheaper than their secondary counterparts (Kiehne 2003).

Secondary batteries are commonly called "rechargeable." The chemical reaction that is used to produce electricity is reversible which enables the recharging feature of the battery. These batteries can be recharged multiple times with little change in their capacity. There are many different types of secondary batteries.

Each type of battery is typically named for its main components. Some of the more common types of batteries are lead-acid, nickel-cadmium (NiCad), nickel-metal hydride (NiMH), zinc-air, and lithium-ion. While the names give an idea of the chemical composition of the battery, even batteries that use the same principal reactions can differ from each other in physical size and electrical power.

The primary reaction that occurs in a battery typically involves the materials for which it is named. However, this reaction is not the only reaction that takes place. Because the materials of the battery's construction are not completely pure, secondary reactions take place as well. The impurities interfere with the primary chemical reaction and reduce the total power output of the battery and/or its recharging capacity (Martin 1974).

Batteries work because of reactions that produce electrons. These reactions are typically called reduction-oxidation (REDOX) reactions and are actually composed of two separate reactions: a reduction reaction and an oxidation reaction. A reduction reaction requires additional electrons to be completed, and an oxidation reaction produces electrons when it occurs (Raposa and Glover 1983).

Batteries are designed so that the electrons that are required for the reduction reaction are produced by the oxidation reaction. The construction of the battery assures that for the electrons to get from one reaction to the other, there must be a connection between the positive and negative terminals of the battery. The positive electrode is where the reduction reaction takes place, and the negative electrode is where the oxidation reaction takes place.

The exact voltage that is produced by a battery is controlled by the particular chemical reaction. A lead-acid battery cell produces about 2 volts while a lithium-ion cell produces about 3.6 volts. When these voltages are too low to power the attached circuit, multiple battery cells are connected in series until the desired voltage is reached. A typical automobile battery is composed of six lead-acid cells connected in series to provide the 12 volts that the electrical system runs on (Kiehne 2003).

2.3.2 Batteries Used for Traction

In the case of traction applications, there are some important issues that need to be considered when battery power is an option. The types of situations that will be encountered provide specific criteria on the design of the power system. For low horsepower movement and areas where emissions must be avoided, battery power is a good choice. For situations that require long periods of high power production or long-range operation, battery power is a less feasible option (Kiehne 2003).

Battery powered vehicles have benefits that include low noise, small vibrations, simplified transmission systems, and reduced pollution when compared to combustion engines. A disadvantage of battery powered vehicles is that they are either heavy because of the use of inexpensive and low energy density lead-acid batteries, or they are expensive because of the use of lighter weight, higher energy density, but more expensive batteries (Kiehne 2003). Weight may not be a problem when traveling on level ground or at low speeds as it can provide extra traction.

2.3.3 Maintenance

Batteries require periodic maintenance to insure that they continue to work safely and at peak efficiency. Maintenance tasks include checking electrolyte level and temperature, removing corrosion on battery terminals, electrical capacity checks, and leak checks. The exact scheduling of these tasks depends on the battery system in use and the environmental conditions experienced. These tests are part of a regular vehicle maintenance schedule. As with most routine maintenance, proper scheduling and diligence will ensure that the equipment continues to perform acceptably without the need for replacement (Kiehne 2003).

Possible failures of battery storage systems include loss of capacity, leaking, and explosion. Of these, leaking is mainly caused by environmental damage such as large physical shocks and abuse. Leaking electrolyte generally requires that the battery be replaced which can be a costly and time-consuming procedure. In addition to this, electrolytes are often highly corrosive. It can pose a structural hazard to the vehicle, an environmental hazard if it reaches the soil, and a safety hazard if workers come into contact with it.

The other common battery failures are caused by thermal effects. These can occur either due to external environmental temperature changes or internal changes. While environmental temperature changes are difficult to control without active cooling or heating systems, the internal temperature changes are mostly caused by charging and discharging cycles. Extreme temperatures can cause a reduction in the total capacity of the battery. These situations must be taken into account when choosing a battery type because each battery reacts differently to temperature fluctuations.

The way in which a battery is charged also affects it capacity. For each battery type there is an optimal charging and storage regimen. The consequences of not following this set procedure can depend on the battery type and range from reduced battery capacity to explosion because of gas buildup. Charging batteries with a liquid electrolyte releases hydrogen and oxygen from the electrolysis of water. If the rate of charging is too great, the gas that has been produced cannot escape from the battery housing fast enough to eliminate pressure buildup. An explosion may occur if this pressure becomes too great. There is also a danger of explosion from a spark igniting the hydrogen and oxygen mixture. For this reason, batteries used in industrial settings need to be either of the sealed variety or located in an area with good ventilation (Kiehne 2003).

CHAPTER 3: DYNAMIC BRAKE ENERGY RECOVERY POTENTIAL

A critical aspect of the cost effectiveness of a system for dynamic brake energy recovery on locomotives is the total amount of energy available. If only a small amount of energy is available, then no project is likely to be cost beneficial. As the amount of recoverable energy increases, so does the potential for a feasible project. I used two methods to analyze the amount of energy available for recovery: locomotive event recorder data and simulation.

The first method involved use of data from event recorders on locomotives operating in various trains over a route. These data are downloaded from the locomotive at set locations throughout the railroad's system. Event recorder data enables the analysis of how a specific train performed along its route including the amount of dynamic brake use. The main advantage of this approach is that it is an analysis of actual operating data and necessarily takes into consideration the operational constraints that were present at the time. These constraints can include delays due to traffic or track maintenance and the actions of the locomotive engineer. The analysis of event recorder data also allows validation of simulation techniques.

Since event recorder data are only available for previously completed journeys, use of this method does not necessarily allow prediction of how trains will perform on different routes or even on the same route under different circumstances. Event recorder information also does not necessarily allow forecasting of how changes in operating conditions such as different numbers of locomotives or consists will effect the energy available for recovery.

The second evaluation method used was simulation of train operations using the Association of American Railroad's (AAR) Train Energy Model (TEM) software. This software has been developed so that train operations and fuel consumption can be analyzed. The software provides flexibility in constructing a consist and running it over a section of track of the operator's choice. As with all computer simulations, the results of the program should be compared to actual data in order to validate the results.

3.1 Locomotive Event Recorder

Locomotives that travel faster than 30 mph are required by the Federal Railroad Administration (FRA) to be equipped with event recorders, primarily to aid in the investigation of accidents. They must record the status of a specified set of locomotive characteristics (Table 3.1) every second and have adequate capacity to store at least 48 hours worth of information.

Time
Speed
Direction
Distance
Throttle position
Brake applications
Air
Independent
Dynamic

Table 3.1 FRA required parameters for locomotive event recorders

FRA requirements specify the minimum data set that must be recorded, but railroads have found it useful to record other data as well. Typical recorders capture 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.).

The position of the train is not recorded, so this information must be determined using waypoint time stamps from the railroad system. Once the time stamps on the event recorder are calibrated against waypoints, the position of the train along any portion of its recorded journey can be extracted. After the determination of a train's location, information such as speed, throttle notch setting, dynamic brake setting, and dynamic brake current can be extracted for analysis.

3.2 Train Energy Model (TEM)

For a study focused on the dynamic brake energy recovery potential for locomotives, a model that could give a close approximation to the real-world dynamic brake usage for a given train is beneficial. Such a model would enable the study of different scenarios without incurring the time and operating costs of actually running the train consists over a given section of track.

The AAR’s Transportation Technology Center Incorporated (TTCI) has created simulation programs for the railroad industry to assist in the study of rail related issues (TTCI 2005). The current programs available for use in the railroad industry are NUCARS, TEM, RTLM, WRTOL, TOES, and STARCO. These programs each simulate different aspects of the railroad environment. The areas covered include vehicle ride response (NUCARS, TOES, and STARCO), track wear (RTLM and WRTOL), and coupler forces and braking (TOES and STARCO). For the purposes of this research, the Train Energy Model (TEM) is most applicable.

This program simulates the energy required to run a specific train over a specific route. The route data are imported into the program, and once the locomotives, car type, lading weight and operating requirements for a consist have been entered into the program, the train's characteristics can be simulated as it runs over the route. The simulation acts in the role of an engineer by adjusting the throttle and brake applications to keep the train under the speed limit while avoiding unduly large draft and buff forces (Singh 1995). These duties are handled by the Generalized Algorithm for Train Control (GAT).

3.2.1 TEM Features

Adjustability is the main feature of the TEM software. Train consists and ladings are configurable by using a graphical interface. Different locomotive and car types can be chosen to replicate the consists seen in service. New car types that are not included in the program can also be created using graphical tools.

Routes can be imported based on actual data that includes speed limits, grades, and curves. These routes can then be used in the simulation of any consist that has also been created. The train control can be modified to simulate starts and stops or to limit operation to only a portion of the track segment.

3.2.2 TEM Output

After a simulation has been run, the train speed and track speed limit are displayed as a function of the milepost along the track for the segment simulated (Figure 3.1). This gives an overview of the performance of the GAT with respect to staying beneath the posted speed limit. Further information about the energy usage of the train and its speed at a given time is available to enable an in-depth analysis.

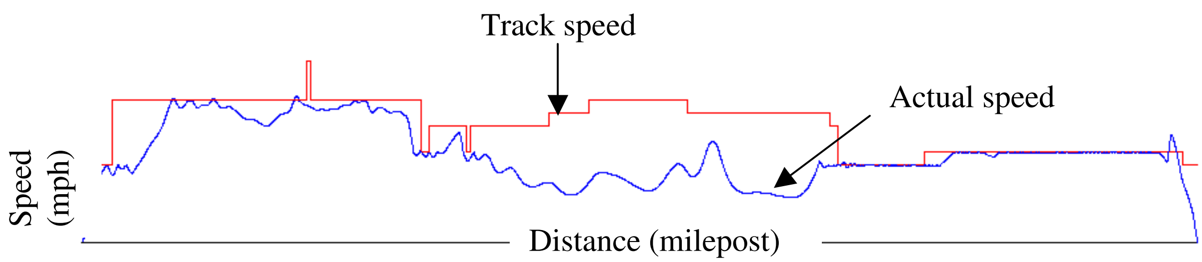


Figure 3.1 Example of speed profile output from TEM (with information added)

TEM also produces a summary report for each run of the simulation. This summary provides information such as the number of locomotives and cars in the consist, the total weight of the train, and the amount of fuel consumed (Figure 3.2). Also provided is a summary table of “WORK DONE by EACH FORCE” which represents the energy produced by each simulated force acting on the train (Figure 3.3). In the analysis I conducted, the figure for energy produced by the dynamic brakes was taken from this portion of the summary report.

```
T E M  FUEL and ENERGY REPORT for SIMULATION 2-M-SdgBar103a

                    OPERATIONS SUMMARY
___________________________________________________
            CONSIST 2-M-SDGBAR103A
   No. Vehicle Blocks in Consist           76
       No. Locomotives                      3
       No. Operating Leading Locomotives    3
       No. Cars and Nonoperating Locos     73
       No. Operating Helpers                0

 Total Train Length                  4048 feet

  Total Train Power (at the rail)    12432 hp

 Total Train Weight                  4903 Tons
     Weight of Fuel                     0 Tons
     Weight of Lading                2040 Tons
     Empty Train Weight              2863 Tons

Maximum Power/Weight                2.51 hp/Ton

              TRACK   DIST76EED
   No. Stops                                1
  Total Distance Traveled        83 mi 1044 ft

   Total Elapsed Time           2 h 30 m 51 s
       Over-the-Road Time       2 h 30 m 37 s
       Dwell Time               0 h  0 m 14 s

  Average Over-the-Road Speed          33 MPH

  TOTAL FUEL CONSUMPTION              899 gal
    Diesel Fuel/Work                 71 gal/MWh
```

Figure 3.2 Summary report for simulation generated by TEM

WORK DONE by EACH FORCE

Force	Work(kWh)
Gravity	-3538.6
Resistance	-4882.5
Air Brakes	-1078.8
Dynamic Brakes	-3235.7
Diesel Traction	12728.9
NET WORK	-6.8

Figure 3.3 Summary report from TEM showing simulated work produced by each force

3.2.3 Previous TEM Validation

As with any model, its output must be tested to make sure that it accurately simulates real world situations and that future results can be used with confidence. In 1992, a validation of the fuel consumption portion of the TEM program was completed (Drish and Singh 1992). For this test, two trains were modeled in TEM. The results of the simulation were compared with the actual event recorder and fuel ticket totals for the trains in normal service.

The first train was a unit coal train. The route over which it ran was approximately 570 miles of "undulating and sinuous" terrain (Drish and Singh 1991). The maximum grades seen were –2.1% and 3.0% with a maximum curvature of 11.0 degrees. This consist was analyzed on both the empty and loaded portions of its journey. The round trip total fuel consumption was then compared to the TEM simulated results.

For the actual train, the roundtrip consumed 8,813 gallons of fuel based on the fuel tickets. TEM simulated the fuel usage as 7,242 gallons of fuel. The discrepancy between the two values can be partially attributed to the TEM result not accounting for all of the activity that occurred during the trip such as idling in sidings and loading and unloading movements. The fuel requirement for this extra activity was estimated to be 1,287 gallons. When this is added to the TEM total, it brings the two values to within 284 gallons, or 3%, of each other.

While fuel consumption estimation is a useful measurement, the train controller must also be analyzed. The duty cycle from both the TEM simulation and the event recorder data were compared based on the amount of time that the locomotive was operated in dynamic braking mode, low throttle settings (run 0 to 4), and high throttle settings (run 5 to 8). The event recorder data showed that the fraction of the time in each was 29%, 41%, and 30% respectively. This compares to the results from TEM of 0%, 48%, and 41%.

The duty cycles for the simulated and actual events varied substantially. The discrepancy can be attributed to the way in which the train control program operated the train. The controller tries to maintain its speed by utilizing the idle (run 0) position instead of the dynamic brake whenever possible. This is different from the actions of actual locomotive engineers who reduce the throttle and use the dynamic brake more deftly when controlling the train.

The second test involved a mixed intermodal train. This train was simulated as four separate consists because cars were set out along the route that was to be analyzed (Drish and Singh 1992). This train was run approximately 355 miles over "undulating and essentially tangent" terrain that included grades between –2.0% and 1.7%. The maximum curvature for the track was 6.0 degrees.

The fuel consumption for the actual train was 2,307 gallons, while the TEM result was 2,186 gallons. The difference is 121 gallons, or 5%. As observed in the previous test, the duty cycle comparison for this second train showed substantial variation in the use of dynamic and air brakes (respectively, event recorder 5.5% and 31.6% and TEM 17.7% and 13.7%).

3.3 Event Recorder and Train Energy Model Comparison

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, data on the dynamic brake characteristics of trains traveling over Cajon Pass on the BNSF Railway were obtained from the railroad.

Prior studies have shown the validity of both the fuel consumption and train handling algorithms contained in TEM (Drish 1992, Drish and Singh 1991 and 1992), but the portion of the program that simulates dynamic brake usage and energy production had not been validated. I conducted a validation analysis by comparing the output of the program with actual train event recorder data. The BNSF Railway provided detailed route data for the Cajon Pass portion of their southern transcontinental main line, as well as train consist and locomotive event recorder data for 21 trains traversing this route.

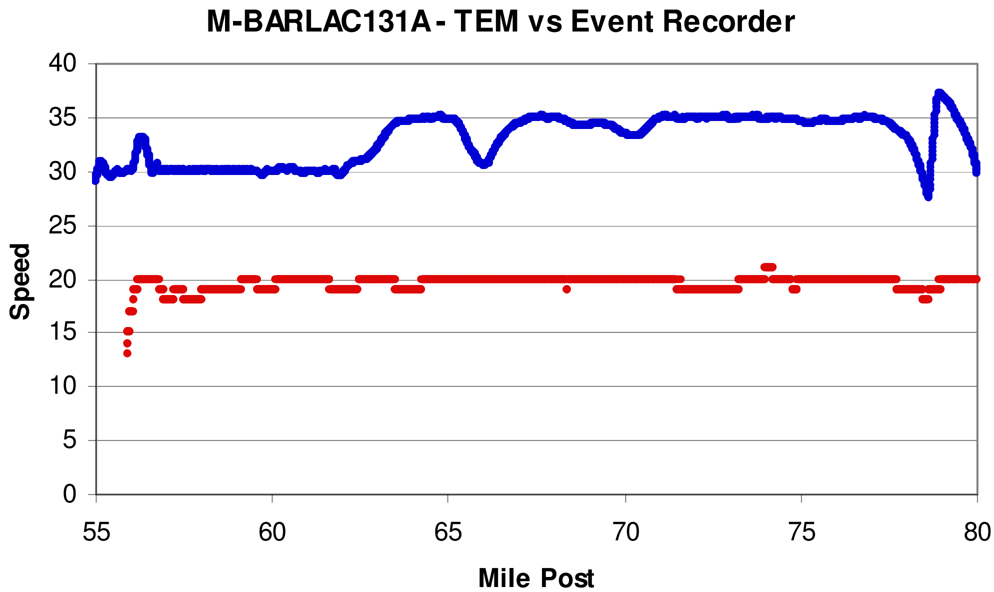
The locomotive event recorder data were from the onboard Wabtec recorders and viewed using Wabtec's event recorder analysis software. These data were analyzed to extract the dynamic braking characteristics of trains traveling between Barstow and San Bernardino, CA.

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 amp-seconds for the journey. Using an estimate of the resistance of the dynamic braking grid of 0.435 ohms (Runion 2005), the power dissipated through the grids was calculated. Table 3.2 shows the comparison between simulated and calculated dynamic brake energy dissipation.

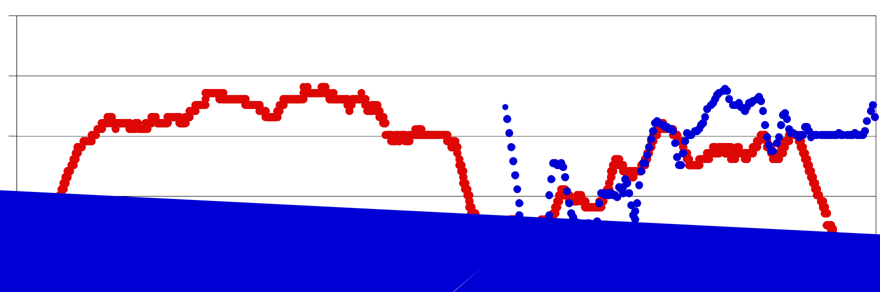
Train Symbol	Event Recorder	TEM	Difference
M-BARWAT120A	2,592	2,362	230
M-BARLAC131A	1,244	1,083	161
M-BARSDG131A	692	968	-276
M-BARWAT131A	2,744	10,204	-7,460
M-BARWAT130A	155	1,375	-1,220
M-SDGBAR101A	800	6,100	-5,300
M-SDGBAR128A	237	3,177	-2,940

Table 3.2 Comparison of actual versus simulated dynamic brake energy for seven trains

The dynamic brake totals for the trains exhibit large variability. These differences may 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 use the air brake only when more braking is required (Drish 1992). 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. 3.4).


M-BARLAC131A - TEM vs Event Recorder
Speed
40
35
30
25
20
15
10
5
0
55
60
65
70
75
80
Mile Post

(a)



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-BARLac131A [Table 3.2, Fig. 3.4a]). Also, trains that showed very similar speed profiles did not have similar dynamic brake values (e.g. M-SDGBAR128A [Table 3.2, Fig. 3.4b]). Without knowing the constraints on the analyzed trains due to other traffic moving on the line or other factors, accurate simulations were not possible.

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.

3.4 Applicable Train Types

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 Cajon 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.

Based on data provided by BNSF for a three-month period between November 2004 and January 2005, Cajon Pass has an average of about 80 total trains per day (Table

4.2). The data consisted of waypoint reports from stations along the route and included train symbol, train type, and time of its passage.

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 3.3 Daily distribution of traffic for Cajon Pass

Of the 80 trains per day over the pass, only the lower priority trains could feasibly be stopped in a yard to add locomotives equipped for energy recovery. The highest priority trains on the BNSF system are the “Z”, “Q”, “P”, and “S” intermodal trains. These trains alone account for half of the traffic over the route. Removing these trains along with the Amtrak and unit trains leaves 34 trains per day as candidates for use of an energy recovery system.

3.5 Event Recorder Analysis Results

3.5.1 Methodology

The data that are exported from the Wabtec event recorder analysis software do not directly provide information on the amount of energy dissipated by the resistor grids.

This must be calculated using the information from the event recorder and other external sources.

The dynamic brake data recorded by the event recorder only shows when the dynamic brake was in use and the amperage to the resistor grids. Since the data are recorded at one-second intervals, the summation of the amperage readings while the dynamic brake is in operation provides a total of the amp-seconds produced by the system.

To convert the total number of amp-seconds to energy, the resistance of the resistor grid must be known. Recalling that energy is power multiplied by time, and that power is found by using amperage and resistance, energy is calculated as follows:

$$E=Pt$$

Where: E = energy
P = power
t = time

$$P=I^2R$$

Where: P = power
I = current (amps)
R = resistance (ohms)

From the event recorder, the amperage and time are available, so the only remaining variable is the resistance of the grid, which is 0.435 ohms (Runion 2005). Using this formula, the data from the event recorder can be converted to total energy available for recovery.

3.5.2 Sample Analysis

When the data are exported from the event recorder software, it is in the form of a very large table similar to Table 3.4 that shows only 38 seconds of operation. Once the proper segment has been extracted, the only necessary columns are: “Load” and “Dyn Brake.” When the dynamic brakes are in use, the “Dyn Brake” column will show “D1” through “D8” depending on the level of braking.

To analyze the amount of energy produced by the dynamic brakes, the data in the “Load” column is summed anytime the brake is in use. Since the data are recorded once per second, this sum is then the total amp-seconds produced by the dynamic brakes. This figure is squared and multiplied by the resistance of the resistor grid to give the total watt-seconds produced.

From Table 3.4, the dynamic brake was used for 18 seconds. Summing the load at these records gives 2,552 amp-seconds. When squared and multiplied by the resistance of the grid (0.435 ohms), the total is 2,833,026 watt-seconds (787 watt-hours.)

Date	Time	Milepost	Load (amps)	Throttle Notch	Dyn Brake
6/29/2005	8:09:48	32.11	144	Off	D2
6/29/2005	8:09:49	32.1	144	Off	D2
6/29/2005	8:09:50	32.09	144	Off	D2
6/29/2005	8:09:51	32.08	144	Off	D2
6/29/2005	8:09:52	32.07	144	Off	D2
6/29/2005	8:09:53	32.06	144	Off	D2
6/29/2005	8:09:54	32.05	144	Off	D2
6/29/2005	8:09:55	32.04	144	Off	D2
6/29/2005	8:09:56	32.03	144	Off	D2
6/29/2005	8:09:57	32.02	144	Off	D2
6/29/2005	8:09:58	32.01	144	Off	D2
6/29/2005	8:09:59	32	144	Off	D2
6/29/2005	8:10:00	31.99	144	Off	D2
6/29/2005	8:10:01	31.98	144	Off	D2
6/29/2005	8:10:02	31.97	136	Off	D1
6/29/2005	8:10:03	31.96	136	Off	D1
6/29/2005	8:10:04	31.95	136	Off	D1
6/29/2005	8:10:05	31.94	128	Off	D1
6/29/2005	8:10:06	31.93	24	Idle	Off
6/29/2005	8:10:07	31.92	8	Idle	Off
6/29/2005	8:10:08	31.91	8	Idle	Off
6/29/2005	8:10:09	31.9	8	Idle	Off
6/29/2005	8:10:10	31.89	8	Idle	Off
6/29/2005	8:10:11	31.88	8	Idle	Off
6/29/2005	8:10:12	31.87	8	Idle	Off
6/29/2005	8:10:13	31.86	8	Idle	Off
6/29/2005	8:10:14	31.85	0	Idle	Off
6/29/2005	8:10:15	31.84	0	T1	Off
6/29/2005	8:10:16	31.83	0	T1	Off
6/29/2005	8:10:17	31.83	0	T1	Off
6/29/2005	8:10:18	31.82	0	T1	Off
6/29/2005	8:10:19	31.81	72	T1	Off
6/29/2005	8:10:20	31.8	72	T1	Off
6/29/2005	8:10:21	31.79	72	T1	Off
6/29/2005	8:10:22	31.78	72	T1	Off
6/29/2005	8:10:23	31.77	72	T1	Off
6/29/2005	8:10:24	31.76	72	T1	Off
6/29/2005	8:10:25	31.75	72	T1	Off

Table 3.4 Sample data from event recorder

3.5.3 Results from Analysis

The event recorder data for the 21 "M" trains were analyzed. Of these, five trains had incomplete data that did not permit analysis. The remaining trains consisted of runs in both directions over Cajon Pass. The portion of their journey between Barstow and San Bernardino, CA was exported and the information summarized (Table 3.5). These trains had differing number of locomotives, cars, and helper units as well as total weights.

Train Symbol	Locomotives	Cars	Loads	Gross Weight (tons)	Dynamic Energy (kWh)	Time (h:m)	Direction
M-SdgBar101a	5	56	31	4,802	800	3:49	East
M-SdgBar128a	3	105	20	5,463	237	2:50	East
M-SdgBar103a	3	73	19	4,284	313	5:36	East
M-SdgBar116a	6	90	14	1,946	833	3:35	East
M-WclBar124f	5	69	12	3,401	324	2:36	East
M-WclBar125f	3	80	16	4,217	426	1:32	East
M-WclBar126f	4	48	11	2,644	45	0:48	East
M-WclBar128f	5	44	11	2,488	0	3:46	East
M-BarLac131a	4	109	106	12,976	1,244	4:25	West
M-BarSdg131a	4	35	32	3,767	692	3:34	West
M-BarWat120a	6	78	76	9,543	2,592	3:30	West
M-BarWat131a	8	76	49	7,176	2,744	4:39	West
M-BarLac101a	3	44	44	5,439	574	3:34	West
M-BarLac113a	5	60	58	6,739	1,327	4:25	West
M-BarLac110a	6	107	107	13,907	1,306	4:49	West
M-BarWcl121f	3	29	21	3,009	1,176	4:38	West
Averages							
Total	5	69	39	5,738	915	3:37	
East	4	71	17	3,656	372	3:04	
West	5	67	62	7,820	1,457	4:11	

Table 3.5 Results of dynamic brake energy production for "M" trains operating over Cajon Pass

CHAPTER 4: COST JUSTIFICATION BASED ON FUEL SAVINGS

In order to assess the cost effectiveness of the development and implementation of an energy recovery program, the value of the energy must be calculated. In the context of this research, this primarily means translating the energy figures into units of diesel fuel.

4.1 Efficiency of Energy Recovery

The average dynamic brake energy calculated from event recorder data (Table 3.5) was 915 kWh per train. This value is the average energy produced by all of the dynamic brakes in the locomotives of a train. This value does not account for losses in any recovery or reuse process. It also does not account for any operational consideration that may reduce the total amount of energy recovered or reused.

For recovery, the storage system can be expected to have an average efficiency of approximately 75% (United States Department of Energy, Federal Energy Management Program 2003). This efficiency includes the losses due to energy conversion and storage for the system. The electric traction motors on locomotives are about 80% efficient (Ostlund 1998). Combined, the efficiency of the recovery and reuse process is 60%.

The reduction in available energy for reuse due to losses in the conversion processes reduces the values shown in Table 3.5. With this reduction included, each train has the potential to recover an average of 549 kWh (Table 4.1) and each locomotive the potential to recover 182 kWh.

	Energy (kWh)	
Train Direction	**Per Train**	**Per Locomotive**
Eastward	223	93
Westward	874	291
Average	549	183

Table 4.1 Energy recovery and reuse accounting for energy loss

For maximum energy recovery, every locomotive in a given train would have to be capable of use with an energy storage system. It may not be practical to exchange every locomotive on an inbound train with one modified for energy recovery. While traveling over the route, regular locomotives could be used in conjunction with modified locomotives.

The use of both regular and modified locomotives would reduce the amount of energy recovery since only the modified locomotives would be recovering and reusing energy. To account for this, a 50% reduction to the average available energy recovery per train is made in the following calculations. This figure assumes that half of the locomotives on each train would be replaced with locomotives that had been modified for energy storage. The total efficiency of recovery is then 30% (Table 4.2), and the estimated average recovery per train is 275 kWh.

Component	**Recovery Efficiency**
Equipment Utilization	50%
Storage System	75%
Traction Motors	80%
Total	30%

Table 4.2 Efficiencies of system components

4.2 Energy Storage System Cost

The primary cost of an energy storage system is the capital investment. The capital includes both the rolling stock to house the system, and the system itself. These costs can be estimated to assess the likely effectiveness of such a system.

It would be unlikely that a new boxcar would be purchased to house the energy storage system. This assumption is based on the premise that no major modifications would be required on the car's structure. Using an old car would reduce costs and provide as adequate of a housing as a new car would, and its value is determined based on its scrap value.

A standard 263k car has a gross rail load of 263,000 pounds and typically weighs 60,000 pounds empty. With the current price for scrap steel at $370/ton (Grede Foundries 2006), a used boxcar can be assumed to have a scrap value of $11,000. To this, an additional $9,000 worth of work would be done in rehabilitation.

The major portion of the capital cost involved with an energy storage system is the actual energy storage device itself. Estimates for the cost per kilowatt-hour of storage range from $100/kWh to $600/kWh (United States Department of Energy, Federal Energy Management Program 2003, VBR Power Systems 2006) with the lower estimates for large utility installations. For this mobile application, the median figure of $300/kWh is used. A system storing twice the average estimated energy recovery, 550kWh, would then cost $165,000 per storage vehicle.

The total cost for the initial capital outlay is $176,000 per unit not including labor costs for vehicle construction. Labor costs are estimated as 20% of the capital cost (United States Department of Energy, Federal Energy Management Program 2003), and inclusion of these costs brings the total vehicle price to $220,200 (Table 4.3). This cost is a preliminary estimate using general figures and is subject to change based on more specific figures for equipment and labor cost.

Vehicle	
Empty weight (lbs)	60,000
Scrap steel price ($/ton)	$370
Car cost	$11,000
Rehabilitation	$9,000
Storage System	
Energy capacity (kWh)	550
Cost per kWh	$300
Storage cost	$165,000
Labor	
Labor cost (20%)	$35,200
Total vehicle cost	$220,200

Table 4.3 Energy storage vehicle cost breakdown

4.3 Cost Estimation of Full-scale Implementation

The total number of energy storage vehicles required for a full-scale implementation is dependant on the number of trains equipped per day and the amount of time required to add and remove the equipment. Assuming that the 34 trains per day are equally spread out throughout the day, one train would depart every 42 minutes. With an average transit time of 3.5 hours between Barstow and San Bernardino (Table 3.4), five trains are in transit at a time. Adding an additional hour to each end of the journey first to add and then to remove the energy storage vehicles, the total transit time for one train would be 5.5 hours. During this time, eight trains would be either en route or in the yards waiting for the addition or removal of the vehicles. Having eight vehicles in transit at any one time and one extra set of vehicles at each yard for protection and allow for imbalances in traffic flow brings the total number of required vehicles to ten, and thus the initial capital cost is $2,202,000 (Table 4.4).

Applicable trains per day	34
Average headway (minutes)	42
Average time over pass (hours)	3.5
Yard dwell time (hours)	
Adding vehicle	1
Removing vehicle	1
Total transit time (hours)	5.5
Trains concurrently in process	8
Extra storage vehicles	2
Total storage vehicles	10
Cost of vehicle	$220,200
Total cost of vehicles	$2,202,000

Table 4.4 Summary of parameters affecting full-scale storage vehicle cost

4.4 Fuel Savings

From the point of view of a railroad, the primary benefit of an energy recovery system is a reduction in fuel consumption. The energy recovered is energy that does not need to be provided by the combustion of diesel fuel. Data from both TEM and the BNSF Railway (Stehly 2006) estimate the useful energy from one gallon of diesel fuel burned in a locomotive is about 13 kWh, which converts to 74 gallons per MWh.

From the analysis of energy recovery, an average of 275 kWh of usable energy could be recovered per train. For 34 trains per day (Table 3.3), the annual energy benefit would be 3,400 MWh, which converts to a savings of 256,000 gallons of fuel per year.

The cost savings from this reduction in fuel consumption varies based on the price of fuel. For the past four years, the amount that railroads pay for fuel has been increasing (Figure 4.1). The most recent fuel price from 2005 is $1.66 per gallon (Association of American Railroads 2005), and the price is expected to continue to increase in 2006. At this price, the recovery of energy would benefit the railroad $425,000 (Table 4.5).

Reused energy	Fuel reduction	Cost savings
3,400 MWh	256,000 gal	$425,000

Table 4.5 Annual savings from energy reuse

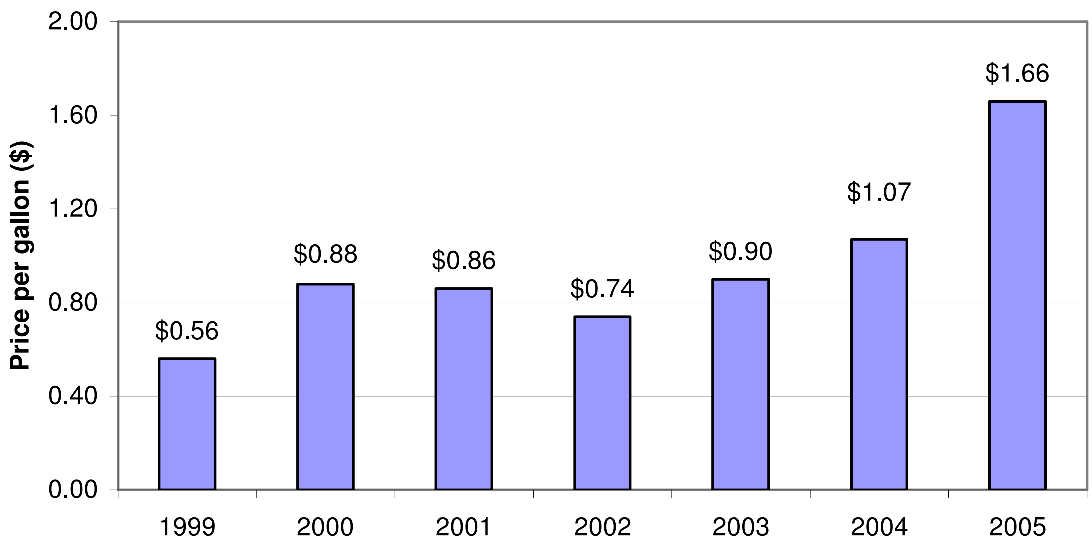


Figure 4.1 Railroad fuel price data (AAR 2005)

While fuel savings are the most direct way to evaluate fuel savings, they are not the only way in which the cost of a system could be recovered. An additional way could be through the monetization of the reduction in air pollution from decreased combustion.

CHAPTER 5: ENVIRONMENTAL CONSIDERATIONS

5.1 Introduction

The cost of pollution has been studied frequently (Mathews and Lave 2000) and the valuation of the different types of pollution varies widely. Also, with each study, the costs may include factors that were not included in the other studies. The available studies also may include factors that are not relevant or lack factors that are important to this project. These factors include: damage to agriculture, buildings or infrastructure, aggravation of existing health problems, increased threat of global warming, and reduced life expectancy.

To produce a valuation for pollution from locomotives, many studies were analyzed and combined to develop an estimate that could be used for preliminary cost analysis (United States Environmental Protection Agency 1999, Funk and Rabl 1999, Mathews and Lave 2000, Sholtz and Wochnick 2000, Perl et al. 2001, Lave and MacLean 2002, United States Environmental Protection Agency 2004, United States Environmental Protection Agency 2005). This estimate was then used to further study the economic feasibility of a locomotive energy recovery system.

5.2 Types of Cost Estimates

When estimating costs, the most accurate estimate is not required for initial feasibility evaluation. The initial filtering of projects can be done with limited estimates that can be done quickly with minimal time and expense. Perry and Chilton (1984) describe two levels of preliminary estimates for deciding if a project shows enough merit to warrant further study. These are "order-of-magnitude" and "study." Both represent high-level studies that have a wide range in accuracy with “order of magnitude” having greater uncertainty than “study” estimates.

An order-of-magnitude estimate has a margin of error greater than +/-30% (Perry and Chilton 1984). The estimate is made using only one main characteristic without consideration of other factors that may be of equal importance. An example of this would be making estimates based on the number of trains a day that pass a point without taking into consideration the type and operational priority of these trains.

The study estimate has an accuracy of +/-30% (Perry and Chilton 1984). This type of study is “Better than order-of-magnitude; requires knowledge of major items of equipment; used for feasibility studies" (Perry and Chilton 1984, pp. 25-64). For this type of estimate, a general idea of the size requirements, capacity, location, utility requirements, and process flow chart are required so that the accuracy of the estimate can be initially constrained.

Perry and Chilton (1984) also describe three other types of estimates. These estimates are "scope, budget authorization, or preliminary," "project control or definitive," and "firm, contractor's, or detailed." The accuracy of these estimates increases progressively. A scoping estimate's accuracy is +/-20% while a detailed estimate has an accuracy of +/-5% (Figure 5.1).

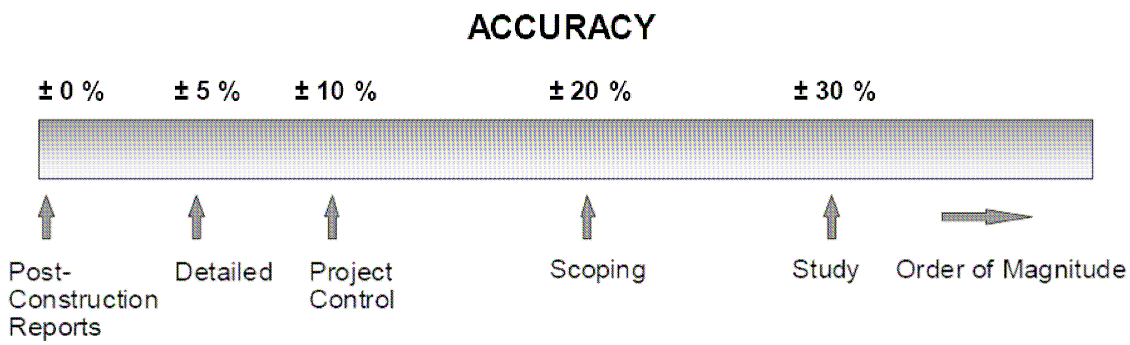


Figure 5.1 Accuracy of cost estimates (EPA 2002)

Governmental regulations are typically based on study level estimates (United States Environmental Protection Agency 2002). They offer an acceptable trade-off between accuracy and expense involved in the estimation process. They have a defined accuracy that is not available with order-of-magnitude estimates and are general enough to provide guidance without accounting for every possible site and situation that could arise. The calculations developed in this thesis should be considered "study" level estimates, and their use for economic feasibility estimation implies that they should be considered accordingly.

5.3 Social Costs

There is a social cost that can be attributed to pollution. The form of this cost can vary. It may be a direct cost in the form of a tax or fee or an indirect cost such as a reduction in crop productivity or an increase in health problems (Matthews and Lave 2000). These are also described as social costs (Lave and MacLean 2002). While direct costs may be easy to quantify, indirect costs can be much more difficult. There have been studies that try to quantify the cost of pollution with regard to the environment, and to the population as a whole. The problem with these studies is that their final results often vary greatly. The variability of the findings can be attributed to the large number of unknowns and corresponding assumptions that must be made in order to reduce the problem to a feasible level. This variability is also affected by location. Air pollution in a rural setting will affect a smaller number of people than the same pollution would in a large metropolitan area. The cost of reduced crop production must be calculated as well as the negative effects on the population's health.

5.4 Governmental Regulations

The topic of air pollution costs becomes an issue with both governments and private organizations in different ways. Governments are concerned with setting standards for the amount of pollution that can be produced by various sources. These standards are based on the health effects that are caused by the pollution (United States EPA 1990). The legislation behind these limits changes as new research is completed and public perception changes. This research provides a basis for taxes, fees, and limits on pollution production.

Along with setting limits for pollutants, fees and fines are also standardized. The fees serve to recoup a portion of the cost to regulate and enforce the stated limits. Fines serve as a deterrent to not complying with laws or regulations. The expense involved in cleaning up pollution can also be included in these fines.

In the United States, the principal federal environmental regulatory organization is the Environmental Protection Agency (EPA). The EPA sets nationwide standards for pollution and fines. In some cases, state and local agencies are allowed to enact regulations that are stricter than the EPA's national level regulations.

Corporations are concerned with the cost of meeting the limits set by the government and also the benefits associated with reducing their total pollution output. These benefits include corporate citizenship and responsibility, improving their public image, reduced liability for health related lawsuits, and profits from selling emissions credits to more polluting companies.

5.4.1 Clean Air Act

In 1990 the federal government completed a wide-ranging revision of the Clean Air Act (CAA) that was first passed in 1970 and revised in 1977 (United States EPA 1990). The new amendments created stricter requirements for the level of pollutants in the air. The 1990 CAA emphasized market based approaches over strict regulation.

The CAA lists six pollutants as "Criteria Air Pollutants": sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), ground level ozone, lead (Pb), and particulate matter (PM). These six pollutants each have limits as to their allowable concentration in the air. The limits were set using health-based criteria (United States Environmental Protection Agency 1996). Within these limits there are two categories. The first is the "primary standard" that protects the health of residents of the area. It is this standard upon which the determination of "attainment" or "nonattainment" areas is based. The "secondary standard" sets limits in order to prevent damage to the environment and property. Attainment areas are those areas that meet set limits for regional pollution levels. Nonattainment areas are those geographical areas in which the air quality is below the set standards. These are the areas that require special programs and controls.

The market-based approach provides incentives for reducing pollution so that industries and consumers will convert to more environmentally friendly practices on their own. It is also performance based because rather than specifying particular pollution control approaches, it allows each individual pollutant producer to find the most cost effective way to reach its reduction goals.

The proposed market based pollution reduction mechanisms range from emissions trading programs, fees, and subsidies to investment funds and public information programs (United States EPA 2001). Trading programs allow stationary pollution sources that can reduce their pollutant output cheaply to sell allowances for the amount of pollution that they produce below their regulated level to sources that have less cost effective methods for reducing their pollution. These allowances or credits are traded on an open market system where the credits are auctioned off. Initially, credit trading programs were only set up for NO_x, but credit programs have now been implemented for SO_x as well and are widely used. Credit trading is not limited to those two pollutants. Credit systems have been set up for lead, particulate mater, volatile organic compounds (VOCs), and other airborne pollutants.

Once a region has been designated as nonattainment, the local environmental governing body must create a State Implementation Plan (SIP). This plan lays out the steps that the state will take in order to meet the CAA requirements. The length of time until compliance, estimated reduction in pollution, and enforcement procedures are all described in the SIP. The EPA must approve each SIP.

Any new sources of pollution in an attainment area must apply for permits before being allowed to operate. These permits allow for control of pollution and require that the new source of pollution is accounted for and can be offset by other reductions in pollution emissions.

While the EPA has the power to enforce the CAA throughout the country, each state is allowed to create and enforce its own air quality laws. The main requirement for these state specific laws is that they be at least as stringent as the CAA. The individual states are then allowed to create laws that take into consideration the special requirements of the local area. However, individual states are precluded from regulating some forms of transportation, notably locomotives, because of the impracticality of these having to conform to different laws as they travel across state boundaries.

Failure to meet the CAA pollution limits within the prescribed period of time can invoke various different forms of penalties (United States EPA 1990). The fines that can be imposed range from $2,000 to $5,000 per ton of excess pollutant released or individual fines not to exceed $25,000 per day. Other sanctions include withholding of federal money for state highway projects that do not serve to reduce pollution generation.

5.4.2 Other Environmental Regulations

Railroad locomotives hold a special place in the requirements of the Clean Air Act. Locomotives and their engines are specifically excluded from the regulations that govern the pollution standards of the nonroad engine specifications (United States EPA 1990). The only guidance that the CAA gives on locomotives is:

> Within 5 years after the enactment of the Clean Air Act Amendments of 1990, the Administrator shall promulgate regulations containing standards applicable to emissions from new locomotives and new engines used in locomotives. Such standards shall achieve the greatest degree of emission reduction achievable through the

> application of technology which the Administrator determines will be available for the locomotives or engines to which such standards apply, giving appropriate consideration to the cost of applying such technology within the period of time available to manufacturers and to noise, energy, and safety factors associated with the application of such technology.

With respect to the guidance given in the CAA, the locomotive regulations drafted by the EPA were completed in December 1997 (United States EPA 1997). Along with the new regulations, the EPA also provided a support document (United States EPA 1998) that laid out the scientific background for the regulations as well as the projected pollution reductions.

The regulatory document set up a tier system for progressive locomotive emission reductions. This system imposes maximum emissions levels based on the year that the locomotive was manufactured or last rebuilt. Imposing regulations this way allowed for a gradual phase-in of emissions reduction technology.

The largest total reductions would come from compliance with Tiers 0 and 1. As emissions technologies advanced and became more affordable, their use would be required to meet the more stringent standards (United States EPA 1998). Because of the differences in the duty cycles of line-haul and switching locomotives, there are two separate standards for each tier (Table 5.1). The largest single pollutant emitted by locomotives is NO_x.

		Standard (g/bhp-hr)			Percent Reduction		
		Tier 0	Tier 1	Tier 2	Tier 0	Tier 1	Tier 2
Line-haul cycle	NO_x	9.50	7.40	5.50	34%	49%	62%
	PM	0.60	0.45	0.20	0%	0%	50%
	HC	1.00	0.55	0.30	0%	3%	47%
	CO	5.00	2.20	1.50	0%	0%	0%
Switching cycle	NOx	14.00	11.00	8.10	28%	43%	58%
	PM	0.72	0.54	0.24	0%	2%	56%
	HC	2.10	1.20	0.60	0%	0%	50%
	CO	8.00	2.50	2.40	0%	0%	0%

Table 5.1 Locomotive emission tier standards and percent reductions (United States EPA 1998)

5.5 Air Pollution Cost Studies

The EPA's Office of Air Quality Planning and Standards (OAQPS) published a document that can be used to provide cost estimates associated with various air pollutants. The *OAQPS Economic Analysis Resource Document* (1999) is provided as a tool to help planners quantify the environmental costs of their current or future decisions. Cost ranges for pollutants are given for volatile organic compounds (VOC), particulate mater (PM), and SO_2. Values for each pollutant are given in dollars per megagram (metric ton).

Since the Clean Air Act (CAA) established the framework for an emission credit trading system, the market value for these credits can also be considered in the cost of pollution. The CAA allows for six types of emissions credits to be traded: VOC, PM, Pb, CO, SO_x, and NO_x.

The credit system is intended to limit the total amount of specific pollutants that are released in a region over a period of time. In this system, called a "cap and trade" system, an upper limit (cap) is set for the total amount of each specific pollutant. The total cap is then divided up among the pollutant emitting industries in the area. Each industry is then allowed to produce that level of the specific pollutant. If an industry produces less pollution than it is allotted, then it is able to sell its remaining amount of pollution in the form of credits. Credits are usually sold in one-ton increments. Theses credits are primarily bought by industries that produce more pollution than they are allotted. Some credits get bought by environmental groups who then retire the credits, so that they are never used for the production of more pollution. The two biggest markets are for SO_2 and NO_X.

Since credits are sold either on a market or by auction, the sale price for a credit is an estimate of the current market value of pollution. This is where credit prices differ from the estimate costs of pollution. The cost for a company to produce more pollution (e.g. the current price of a credit) does not have to be related to the social cost of the extra pollution. There is a wide variation in valuation of the cost of one ton of NO_X and one ton of SO_2 (Table 5.2).

	Price Per Ton	
	NO_x	**SO_2**
Perl et al (2001)	\$1,658	\$658
Perl et al (2001)	\$3,547	\$4,682
Perl et al (2001)	\$2,588	\$1,849
Perl et al (2001)	\$7,673	\$13,166
Lave and MacLean (2002)	\$1,060	
Lave and MacLean (2002)	\$9,500	
Funk and Rabl (1999)	\$18,869	\$33,022
Funk and Rabl (1999)		\$2,595
Funk and Rabl (1999)		\$354
Sholtz and Wochnick (2000)	\$6,000	
USEPA OAQPS (1998)		\$2,571
USEPA OAQPS (1998)		\$11,722
USEPA OAQPS (1998)		\$3,829
USEPA OAQPS (1998)		\$4,568
USEPA (2004)	\$2,500	
South Coast AQMD (2005)	\$13,600	
Mathews and Lave (2000)	\$2,800	\$2,000
USEPA (2005)		\$220
Maximum	\$18,869	\$33,022
Average	\$6,345	\$6,249
Median	\$3,547	\$2,595
Minimum	\$1,060	\$220

Table 5.2 Variation in valuation of pollution

A study by Matthews and Lave (2000) surveyed reports on the cost of emissions. This study also found that there is a wide variation in the estimates for emissions costs (Table 5.3). The values in Table 5.3 are listed in 1992 dollars. The mean values are used for the purposes of estimating the cost of locomotive emissions after being converted to 2006 dollars (Table 5.4).

Species	Studies	Min	Median	Mean	Max
Carbon monoxide (CO)	2	1	520	520	1,050
Nitrogen oxides (NOx)	9	220	1,060	2,800	9,500
Sulfur dioxide (SO2)	10	770	1,800	2,000	4,700
Particulate matter (PM10)	12	950	2,800	4,300	16,200
Volatile organic compounds (VOC)	5	160	1,400	1,600	4,400
Global warming (in CO2 equiv.)	4	2	14	13	23

Table 5.3 Estimated external costs ($/ton of air emissions) (Matthews and Lave 2000)

Species	Median Cost
Carbon monoxide (CO)	738
Nitrogen oxides (NOx)	1,505
Sulfur dioxide (SO2)	2,556
Particulate matter (PM10)	3,976
Volatile organic compounds (VOC)	1,988
Global warming (in CO2 equiv.)	20

Table 5.4 Median cost estimates ($/ton of emissions) adjusted to 2006

5.6 Locomotive Emissions

5.6.1 Emissions Per Time

In order to calculate the cost of locomotive exhaust, the amount of each pollutant produced while the engine is running must be known. Because of the eight running notch system used to control locomotive power output, the calculation of emissions is done in discrete increments. This simplifies the analysis, because the limited number of throttle positions eliminates the need for continuous data measurements throughout the engine's entire RPM range. By contrast, automobile and truck emission studies require calculation across the RPM range making them more difficult.

The data that are available from locomotive event recorders allow a complete understanding of emissions production to be developed. The event recorder data can be used to determine exactly how long each of the throttle positions was used. These data, combined with throttle-notch specific rates of emissions production, can be directly converted into an estimate of total of emissions expelled. A study by Sierra Research and Caretto (2004) provided data on the rate of pollutant production for each locomotive throttle setting (Table 5.5). The eight normal throttle positions are presented along with the idle setting and an average of the production for the dynamic brake setting.

Notch	**Power (bhp)**	**Fuel (lb/hr)**	**HC (g/hr)**	**CO (g/hr)**	**NOx (g/hr)**	**PM (g/hr)**
Brake	117	170	1,400	1,849	1,335	622
Idle	25	32	478	492	309	228
Notch 1	195	78	226	361	1,299	131
Notch 2	400	172	192	464	3,000	140
Notch 3	950	384	361	1,197	7,267	427
Notch 4	1,400	526	294	2,772	14,014	336
Notch 5	2,050	756	595	3,895	25,584	348
Notch 6	2,770	967	748	5,872	33,600	499
Notch 7	3,440	1,180	826	3,302	39,766	585
Notch 8	4,100	1,415	984	3,034	47,027	697

Table 5.5 Locomotive emissions per throttle setting
(Sierra Research and Caretto 2004)

These values, when converted to tons per hour, and combined with the previously introduced cost per ton enable development of figures for emissions' cost per hour. This value can then be used to estimate the social cost of running a locomotive for an hour at each setting (Table 5.6). Social costs do not include the cost of the fuel, the wear on the machine, or the labor costs.

Notch	HC ($/hr)	CO ($/hr)	NOx ($/hr)	PM ($/hr)	Total ($)
Brake	3.07	1.50	2.21	2.73	9.51
Idle	1.05	0.40	0.51	1.00	2.96
Notch 1	0.50	0.29	2.16	0.57	3.52
Notch 2	0.42	0.38	4.98	0.61	6.39
Notch 3	0.79	0.97	12.06	1.87	15.69
Notch 4	0.64	2.26	23.25	1.47	27.62
Notch 5	1.30	3.17	42.44	1.53	48.44
Notch 6	1.64	4.78	55.74	2.19	64.34
Notch 7	1.81	2.69	65.97	2.56	73.03
Notch 8	2.16	2.47	78.02	3.05	85.70

Table 5.6 Calculated social costs per hour of line-haul locomotive operation

The values given in Table 5.6 are for a single locomotive. A typical train crossing Cajon Pass will operate with three to six locomotives, and the calculated figures for emissions cost and other operating costs can be adjusted accordingly.

5.6.2 Emissions from Fuel Use

Another emission evaluation approach is to analyze the pollution generated by burning a gallon of fuel. The EPA has set a series of standards for the amount of pollution that a locomotive can produce (United States EPA 1997). The current standard known as Tier-2 (Table 5.7) applies to all locomotives built after 2004.

Pollutant	Lbs/gal
NO_X	0.2271
PM	0.0079
HC	0.0119
CO	0.0586

Table 5.7 Estimated emission rates for line haul locomotives based on Tier-2 standards (United States EPA 1997)

For a train traveling east over Cajon the recovered energy would equate to a savings of eight gallons per train. Traveling west produces a savings of 32 gallons per train. The savings in fuel and social costs are listed in Table 5.8.

		Savings	
Direction	Fuel	Social	Total
Eastward	$13.28	$1.82	$15.10
Westward	53.12	7.12	60.14

Table 5.8 Cost savings per train traveling over Cajon Pass

Reuse of dynamic brake energy by candidate trains on Cajon Pass has the potential to reduce annual fuel consumption by 256,000 gallons (Table 4.4) and pollution by 40 tons (Table 5.9). Based on the total reduction, a social cost savings of almost $58,000 per year might be achieved.

Pollutant	Reduction (tons)	Social Cost Savings
NO_X	29	$43,600
PM	1	4,000
HC	2	4,000
CO	8	5,900
TOTAL	40	$57,500

Table 5.9 Annual locomotive emissions reductions and cost based on fuel savings.

CHAPTER 6: LEVEL OF JUSTIFIABLE INVESTMENT FOR RAILROADS

From the previous analyses, the energy recovery, cost, and fuel savings of an energy recovery system have been defined based on certain parameters (Table 6.1). Some of these parameters, such as the price of fuel and the value of emissions, are volatile in nature. The benefit received from reduced fuel consumption increases as the price of fuel increases and is an important factor in determining the return on investment (ROI) that a railroad can expect if it invests in energy recovery technology.

Reused energy (MWh)	3,400
Fuel price ($/gallon)	$1.66
Fuel savings (gallon)	256,000
Cost savings	$425,000
Total vehicle cost	$2,202,000

Table 6.1 Summary of fuel and vehicle costs

As currently defined, it would take five years of use to recover the capital cost of the equipment. To be attractive to the railroad, a return on investment of two years is sought. In order to reach this goal, either the costs would have to be reduced or the benefits increased. Assuming that the cost of the vehicle will not decrease, and the efficiency of the technology will not increase dramatically in the near future, then an increase in the price of fuel and thus the value of the savings is the most likely way that benefits may increase.

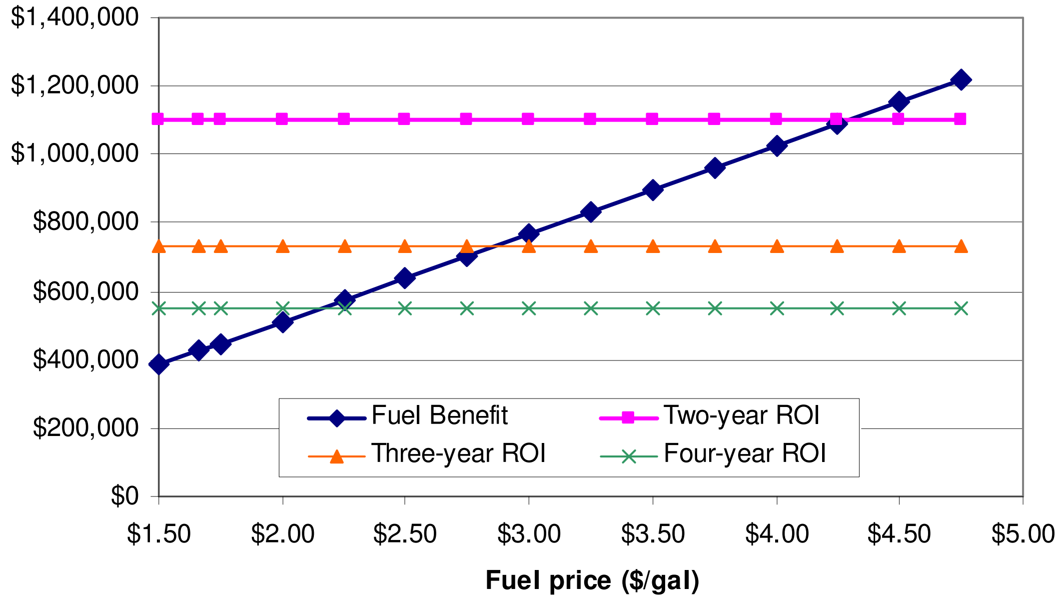


Figure 6.1 Effects of increasing fuel price on meeting various return on investment goals

A two-year ROI would be achieved when the yearly benefit from reduced fuel consumption reaches $1,101,000. Based on current fuel consumption rates, this level of benefit would be met if fuel cost $4.30 per gallon, 2.6 times the current price. Considered another way, at the current price of fuel, the requirement for a two-year ROI could only justify investment of $850,000, which is less than half of the vehicles needed. Relaxing the two-year ROI constraint to three or four years would provide cost justification at fuel prices of $2.87 and $2.15 per gallon, respectively.

When the social benefits (Table 5.7) of this project are included, along with the benefits from reduced consumption, the target fuel price for a two-year ROI is reduced to $4.08 per gallon (Figure 6.2). At current levels, the ROI is 4.6 years, and a two-year ROI would justify an investment of $964,000. Once again, increasing the acceptable ROI would reduce the target fuel price for cost justification to $2.64 and $1.92.

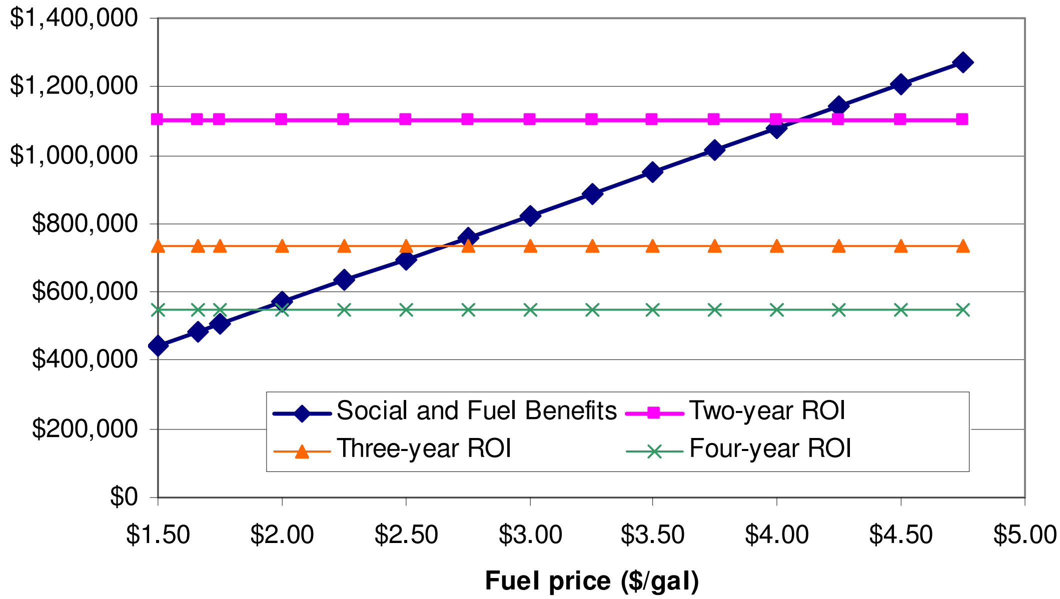


Figure 6.2 Effects of social cost and increasing fuel prices on various ROI goals

Even with the addition of environmental costs, a two-year ROI is still not achievable at current costs and fuel prices. Although fuel prices continue to increase, the levels required for a successful project are unlikely in the near future. Extending the acceptable ROI would ease the constraints on the level of annual benefits required for a justified project. This might be possible with the availability of low interest loans or government grants.

One such grant is California's Carl Moyer Program (South Coast Air Quality Management District 2005). This program gives grants to help fund reductions in NO_x emissions in the Southern California nonattainment area. The program gives up to $3,600 per ton of NO_x eliminated. The BNSF and UP railroads are eligible for this program if the reductions provided are not part of an already agreed upon emissions reduction.

Currently, these two railroads have two such agreements with the State of California, and thus cannot be applied to Cajon Pass operations.

The ROI figures described above are sensitive to the cost of building the vehicle. Any changes in this cost can greatly affect the projected return on investment. Also, the ROI numbers do not include any costs that the railroad might incur from car switching, operations, or maintenance changes that a project such as this may produce. These are costs that the railroad would need to calculate internally to fully understand the possible cost effectiveness of such a project.

CHAPTER 7: SUMMARY

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, as 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. Even when the environmental costs associated with pollution are added, the cost savings does not prove to be sufficiently compelling.

A 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. 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.

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