

Reducing Catenary Costs by Design

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ABSTRACT

Persistence with outdated designs; inexperience of owners, designers, and contractors; and low-volume activity are reasons why catenary costs on some U.S. railroad electrification projects have been unnecessarily high. Conversely, other projects either recently completed or newly bid do show significantly lower costs. Based on this evidence, there is no reason why catenary costs for main-line freight or high-speed railroads should not fall below \$150,000 per single track mile at 1983 prices. In light rail systems, too, current estimates based on California projects show significant savings because of the use of catenary systems rather than old-style tramway overhead. In this paper those factors that are already lowering catenary costs are identified. In due course, as electrification becomes more widespread, as contractors become more familiar with construction, and as railroad engineering and operations staff cooperate with the contractor to speed up installation, three things can occur: catenary costs can come down, the benefits of electrification can be made available to the operators sooner, and much of the conjecture associated with catenary costs can be avoided.

New electrification schemes for main-line operations in the United States are likely to use only a high-voltage system at the industrial frequency of 60 Hz. Around the world, where considerable electrification activity continues, the normally specified voltage has been 25 kV, but 50 kV has been selected on economic grounds, and four 50-kV schemes are currently in operation. Three of these [Black Mesa and Lake Powell Railroad (80 miles), Deseret Western Railway (38 miles), and Tumbler Ridge Branch Line (80 miles)] are in North America and could well provide the operational experience to justify selection of 50 kV as a domestic standard for operating voltage on main-line railroads.

The use of 50 kV is becoming recognized as the more economical system across broad open spaces with no clearance problems, whereas the choice of 25 kV can reduce civil construction costs associated with providing electrical clearances on routes with constricting tunnels or low bridges. The decision by British Columbia Railway to electrify the new Tumbler Ridge Branch Line at 50 kV was taken despite the requirement for 10 miles of tunnels.

Aside from insulators, the design and installation of catenaries is virtually identical for both 25 and 50 kV. Also, ratings for both voltages are commonly 600 to 900 amps, although values up to 1,200 amps may be called for to cater to higher train loadings. However, this does not mean that one standard design is sufficient or even desirable countrywide. Each particular railroad and each stretch of track has its own specific impact on catenary design and hence catenary cost. This also includes voltage selection.

The increased cost of dual-voltage electric locomotives capable of operating at both 50 and 25 kV is relatively small compared with the potential savings in providing additional electrical clearance for 50 kV or the additional substations for 25 kV. There is therefore no serious objection to piecemeal electrification at standard frequency, and every advantage can be taken to tailor each catenary to its location and minimize overall costs.

In addition to these main-line applications, there is currently a noticeable resurgence in light rail transit (LRT) systems. For these systems, the selected voltage is 600 Vdc, or 750 Vdc where the tracks are in city streets. LRT catenaries tend to be of heavier cross sections than main line 25- and 50-kV catenaries in order to handle the higher currents (1,000 to 1,500 amps); consequently, they are more costly.

AREAS FOR COST REDUCTION

For U.S. railroads, considerable opportunity exists for reduction in catenary costs from those of earlier schemes and recent electrification projects. The Deseret Western Railroad in Colorado and Utah and the Tumbler Ridge Branch Line of the British Columbia Railway in Canada both report actual catenary costs in the range \$150,000 to \$180,000 per mile.

In broad terms, cost saving opportunities are to be found in

1. Advance planning of possessions, including rerouting of revenue trains;
2. Longer track possession times for construction;
3. Custom-designed construction equipment;
4. Careful study of existing conditions;
5. Refined system studies;
6. Refined catenary layout based on refined track layout; and
7. Volume production of new generation catenary components.

The degree of cost reduction and the speed with which these will be instituted is dependent largely on the volume of activity and the rate of progress.

As can be seen, these opportunities call for long-range in-depth planning by the railroad and the coordinated approach by all railroad departments with their consultants, namely the catenary and power system designers. The suppliers of conductors and catenary hardware (including poles) make their contribution to reducing costs through competition in the marketplace. To this end, the use of the two-step procurement process, whereby proposals are reviewed by the owner for technical compliance before pricing, has the benefit in that the award can be made to the low bidder without the complications of bid evaluations in areas of doubtful compliance. This bid method was applied to catenary for the Portland LRT and is also being used by Sacramento and San Jose transit authorities.

Contractors have in the recent past shown considerable skill in adapting available machines, especially hi-rails, to undertake work on small contracts. Clearly, large volume work, for example 300 route miles and more, will justify a move to more sophis-

ticated equipment, which being more efficient will increase productivity and permit rapid progress in construction. This in turn will reduce overhead and therefore encourage contractors to be more competitive, thereby further reducing catenary costs.

COST REDUCTION BY DESIGN

Considerable scope exists for economizing with new designs of catenary systems compared with the designs that have been in use for many years. Although these old practices may be desirable for small extensions to operating schemes, they are accompanied by high costs that are often unnecessary on new systems. For example, with the advent of high-voltage power supplies at 60 Hz, the need for heavy three-wire catenaries of the type used on the Northeast Corridor has disappeared. Also, the use on new LRT systems of single contact wire with parallel feeders, commonly used earlier this century on interurban electrifications, is now seen to be unnecessarily costly compared with simple catenary.

Catenary Selection

In modern electrification systems the two-wire simple catenary system, which uses a messenger with the contact wire, has been developed to the stage that speeds in excess of 100 mph are possible with excellent commutation. Sagged simple catenary is in every way more economical compared with earlier three-wire systems. In terms of catenary conductor selection, the choice of contact wire is almost universally copper or bronze. Because bronze can cost up to twice as much as hard-drawn copper, its use is clearly uneconomical, and is now rarely specified except on extensions or rebuilds of existing systems.

The use of hard-drawn copper with its increased conductivity but lower strength has generally been made possible by the adoption of constant-tension catenaries. Although the auto-tensioning gear is an additional cost, constant-tension systems have much improved current collection capability compared with fixed-terminated conductors. It is particularly satisfying to note that economical catenary systems are already available for the speeds of up to 180 mph that are being considered for high-speed lines both in the United States and around the world.

Many different materials are used in messengers. Copper messengers have favor in low-voltage systems for being smaller than their equivalent aluminum conductor steel reinforced (ACSR) messengers, and therefore they are visually less intrusive. However, steel-reinforced aluminum conductors cost less, are lighter in weight, and can carry higher tensions than equivalent copper conductors. Because of the reduced sag of ACSR messengers, the system depth of the catenary--distance between messenger and contact wire at the supports--is less for a given span, thus requiring shorter poles and smaller foundations. In general, higher conductor tensions are preferred for reducing blow-off and improving current collection at higher speeds. Due consideration must of course be given to wire wear and a suitable safety factor.

Long Span Philosophy

Experience has shown that economy in the overhead contact system stems from the principal of using the longest spans. Not only is there an initial cost saving at installation, but there is also reduced maintenance. These savings derive from the need for fewer cross-arms to procure, install, and maintain,

and also because there are fewer poles to install.

However, long spans are only permissible by taking due regard of pantograph security. Pantograph security analysis concerns those design criteria that prescribe the relative position of the overhead system contact wire and the pantograph on the vehicle.

A typical midspan analysis is shown in Figure 1. The actual values for each aspect for any specific electrification system will be based on the selected design criteria.

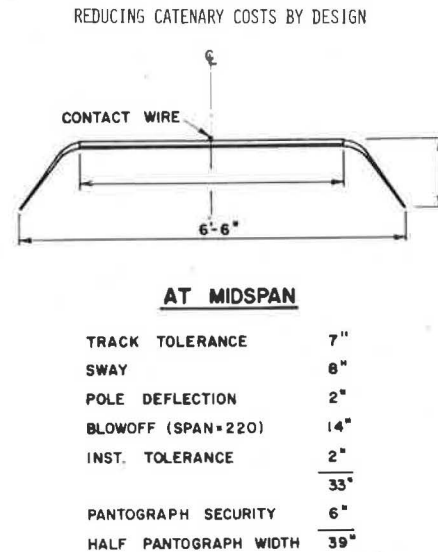


FIGURE 1 Typical pantograph security analysis.

As stated earlier, high conductor tensions reduce wind blow-off, which is the major factor that dictates the maximum span length on auto-tensioned catenaries. Besides high tension, the long spans are obtained by adopting

1. The smallest practical load gauge,
2. Straight tracks and simple track layouts,
3. A wide pantograph (to handle large lateral displacements of the contact wire),
4. Quality track (to reduce the allowance required in the catenary to cater to track tolerances),
5. Quality pantographs with little lateral deflection and satisfactory dynamic response, and
6. Power cars and locomotives with low sway.

In this paper the detail design will be taken one step further, and each of the preceding factors will be described in depth, because these factors are the design bases of economic catenary layout. Later the design approach to pole use and selection and to foundation design are discussed.

DESIGN BASES OF CATENARY LAYOUT

In practical terms, the factors listed in the preceding section may already be stipulated by the owner based on existing conditions and his own approach to electrification. Opportunities do exist to vary seemingly standard requirements in the cases of branch lines and independent lines not connected to the U.S. main-line system. The Deseret Western Railway, which crosses from near Rangely, Colorado, into Utah, is an example. Its special design features are described later.

Load Gauge

One of the most important decisions to be made in developing design criteria for electrification is the height of the load gauge. For dedicated lines and branch lines, the question of maximum load gauge is also colored by the required clearance for out-of-gauge loads. In general, railroads are reluctant to give up any operating capability, and electrification should not be grounds for restricting operations. However, all overhead contact systems are to some extent restrictive, particularly to track and overbridge maintenance operations.

Tunnels will always tend to be a ruling case. Because catenary systems require a minimum space above load gauge of 18 in. for 25 kV and 36 in. for 50 kV, the maximum load gauge in tunnels of standard (23 ft, 6 in.) height above rail is 22 ft for 25 kV and 20 ft, 6 in. for 50 kV, with marginal temporary increases, of course, when the catenary is deenergized. With this in mind, railroads need to examine their operational requirements. To a large extent the movement of out-of-gauge loads and the operation of the intensive service that generally justifies electrification are quite incompatible. Far better that out-of-gauge loads be moved over less-trafficked, lower-speed lines. By adopting a contact wire height of 19 ft, savings up to 10 percent of the number of poles is possible compared to 22 ft, 6 in., as shown in Figure 2a.

Track Layout

Although the cost of straightening tracks is usually prohibitive, there can be marginal cases where the savings in catenary costs could tip the balance that justifies the expense. Straight tracks benefit elec-

trification costs because of the longer spans possible between poles compared with curved tracks. Because of chording of the curve by the contact wire, span lengths are reduced to keep the contact wire within safe working limits on the pantograph head. But the cost of the additional poles can be considerable. Typical 3-degree curves require 35 percent more poles, and 6-degree curves require twice the number of poles required for straight track.

The pole count is also affected by the complexity of wiring required to cater to points, crossings, and turnouts; hence any redesign of the track layout should be coordinated with the overhead wiring. Reduced costs also stem from careful analysis of the actual lines to be electrified, and especially the extent to which yards are wired. Track separation is also important because of the need to accommodate poles.

Track Quality

Track condition is usually defined by FRA track class, and the better the class the less allowance for pantograph sway from track cross-level variations. The track tolerances appropriate to each class of track are given in Table 1.

Although FRA recommends increased quality (reduced tolerances) for increasing speeds on the grounds of safety, definite savings in catenary costs also accrue from reducing track tolerances. The larger the cross-level tolerance, the larger the pantograph sway. Increase in pantograph sway reduces the margin available at the pantograph for blow-out of the wire by wind and the extent that the wire can cut the curve on curved tracks. The better the track class, the fewer catenary supports required. Maintaining track to Class 4 rather than Class 3 tolerances has been shown to save up to 8 percent in

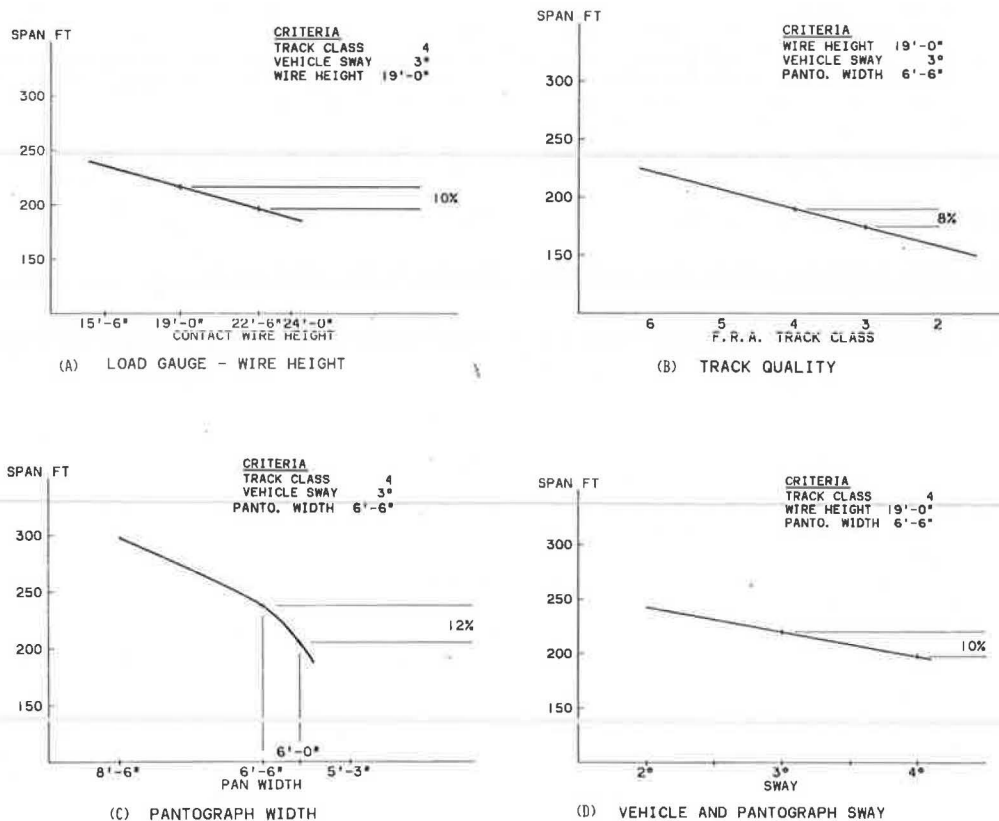


FIGURE 2 Factors that affect span length.

TABLE 1 FRA Classification of Tracks

FRA Class	Train Speed (mph)		Track Tolerance (in.)	
	Passenger	Freight	Alignment	Cross Level
1	10	15	5	2
2	25	30	3	1
3	40	60	1.25	1.25
4	60	80	1.5	1
5	80	90	0.75	0.75
6	110	110	0.5	0.25

the number of open-route poles for the Sacramento and San Jose LRT systems, as shown in Figure 2b.

Pantograph Width

The width of the pantograph has a fundamental relationship to pole spacing, as shown in Figure 2c, and a compromise has to be made between economy in the catenary and any civil reconstruction costs. These costs are associated with the lateral clearance constraints imposed by soffits in some tunnels and overbridges, which limit the pantograph sway envelope. Because it is preferable for locomotives to have unrestricted running capabilities over all main lines, a practical pantograph for general use may only be 6 ft, 6 in. over its head. However, wider pantographs (7 ft, 3 in. at Black Mesa and 8 ft, 6 in. at Deseret) are in use.

As pantographs get wider, they also get heavier, and the increased inertia is a severe disadvantage to maintaining satisfactory current collection at high speed. Certainly for operating speeds up to 100 mph on existing main-line railroads, the 6-ft, 6-in. pantograph with a 10-ft operating height range is acceptable. Reducing the pantograph width by 6 in. for extra high speed may improve current collection, but it will also increase the pole count by about 10 percent.

Vehicle Springing

Vehicle sway from springing, coupled with movement of trucks and side-sway of pantographs, all curtail the width of the collector head available for blow-off and curvature. Harder suspensions, which limit roll to 2 degrees rather than 3 degrees (as is normal), can save 10 percent in the number of poles (Figure 2d). This requirement, of course, only applies to locomotives and cars with pantographs.

POLE USE AND SELECTION

Pole Use

The location of poles between tracks with back-to-back cantilevers has cost benefits compared with pairs of poles installed in track cesses and facing one another. Although track formation width is increased, the required width of the right-of-way can be less as a result of placing poles between tracks.

This factor will become increasingly important as new railroad alignments are studied. Examples in transit systems are already typified in Portland, where LRT tracks are squeezed between the Banfield Freeway and the existing railroad tracks, and also in the Folsom Corridor in Sacramento and in the Guadalupe Corridor in San Jose. Future studies for high-speed trains might well select existing freeway medians by judicious use of the available space.

Pole Selection

The design analysis that permits the use of the smallest pole size is another possibility for saving costs. Catenary poles need not be considered structural columns in the accepted sense of the American Institute of Steel Construction (AISC) design criteria, because the axial loads are minimal in comparison to the bending loads. Hence adhering to AISC code can result in poles that are too conservative, and more precise methods have been developed. For the Pueblo Test Track electrification in Colorado, full-scale tests on selected steel poles were conducted to verify structural adequacy. The poles selected as a result of this approach indicated a 5 percent savings in installed cost of the catenary system than would otherwise have been accepted.

Recent contracts and research into prices for upcoming projects have identified two types of pole to be particularly economical. Each type has prevailed only because of the specific application and specific location of the project. For the Deseret Western Railway, direct embedded wood poles with down guys were used, except for counterweight poles and poles between tracks. For British Columbia Railway, galvanized steel poles fabricated from channel sections were selected. Each pole had a bolted base and was directly bolted to a steel pile cap plate that was welded to the pile after the pile had been driven.

Reinforced-concrete poles can be economical when required in sufficient quantity to amortize the considerable plant investment. Poles for high-voltage systems require that special attention be given to grounding in case of insulator failure, and the poles may have internal grounding cables or special reinforcement detailing to cater to fault currents.

In satisfactory ground conditions concrete poles can be directly embedded without the need for a support foundation. This is a considerable savings in time and material. On the other hand, concrete poles are considerably heavier than steel poles, especially when designed for low deflection values (i.e., pantograph security analysis). This, and the susceptibility of concrete poles to damage in handling, will result in more costly equipment for pole placement than required for steel poles.

FOUNDATIONS DESIGN

None of the poles discussed in the previous section had a requirement for a concrete foundation, but this is not usually the case, and the majority of catenary structures have a concrete foundation of one type or another. In fact, foundations have proved to be a major cost element in many electrification projects, which has prompted examination into alternative foundation designs.

To the experienced eye, concrete foundations for catenary poles on many existing schemes appear considerably oversized. New methods of analysis have been developed in the past 10 years based on pioneering work by staff of the Texas Highway Authority, who studied in considerable detail the design of foundations for the large single-column type destination signs used on freeways.

For unsatisfactory ground, special foundations may be required, and a variety of foundations have been used worldwide. Broadly, the idea must be accepted that, if the track itself can be built on the ground, whatever its condition, then the pole foundations should not require any more special treatment. By careful consideration of the existing conditions, there is no reason why catenary foundations for unsatisfactory ground need be much more costly

than elsewhere. The use of catenary portals with precast slab footings is economical not only for unsatisfactory ground and embankments, but also on embankments composed of large boulders, in which it is difficult to excavate normal foundations without undermining the track. Where subsidence or bank slips are anticipated, these precast slabs have been placed on the top of the ground after it has been leveled off. Subsequent ground failure is manifest by tipping of the slabs (because the portals are connected by pin joints) and has been remedied by re-packing under the slab with track ballast or the like. In this way the high costs of deep-driven piles can be avoided.

The use of a precast concrete sleeve design (1) was found to be satisfactory on a railroad in a remote desert region because of the reduced quantity and quality of site-mixed concrete required compared with regular foundations. This would equally apply on lines with poor off-track access and little time for on-track work because of revenue trains.

RECENT EXPERIENCE

An example of applying these specific design techniques to a recently electrified scheme is provided by the Deseret Western Railway. The selected system for this 38-mile railway, which has severe gradients against loaded trains at the remote end away from the single substation, was 50 kV. ACSR was the selected messenger, with a hard-drawn copper contact wire. By virtue of its isolation from the rest of the U.S. railroad network, opportunity was taken to use an 8-ft, 6-in. wide pantograph and a load gauge appropriate to this coal haul railroad of 17 ft. As a result, span lengths up to 300 ft were possible with complete pantograph security. This reduced the pole count considerably in comparison to the quantity that would have been needed had a 6-ft, 6-in. pantograph been adopted. For 50 kV, cross-arms are costly; therefore, significant savings resulted from the use of the longer spans, which resulted in fewer cross arms.

Reduced maintenance costs are also expected on the Deseret Western Railway as a result of adopting synthetic insulators. This decision was borne out of the need to safeguard the catenary system against vandalism by people with rifles who frequent this stretch of hunting country. The owner also agreed to the use of wood poles because the life of the coal mine is limited. Figure 3 shows the use of wood poles and synthetic insulators on the main line.



FIGURE 3 Deseret Western Railway: 50 kV, simple catenary on main line.

Thus, by optimization of the factors previously discussed, the catenary designer was able to make his contribution to reducing electrification costs. For the Deseret scheme, the installed catenary cost was reported to be on the order of \$150,000 per mile.

As described earlier, 50-kV catenary is in use on the Tumbler Ridge Branch Line in British Columbia. There are two long tunnels on this line--Table Tunnel is 6 miles long and Wolverine Tunnel is 4 miles long. Taking advantage of a reduced load gauge (17 ft), the catenary supports (see Figure 4) were installed 165 ft apart, which coincidentally matched the average span length on the rest of the line.

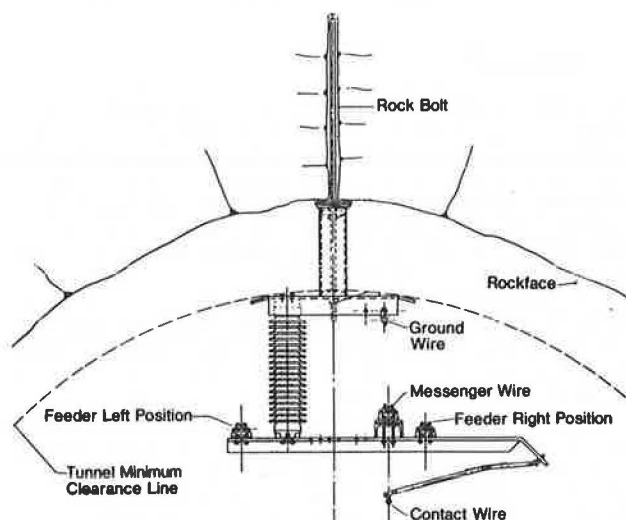


FIGURE 4 Tumbler Ridge tunnels: tunnel support.

Each support consisted of one solid core insulator, whereas three insulators are required on each pole outside the tunnel. Because the tunnels still retain the natural break line of the rock, each of the 300 supports caters to the varying height of the tunnel soffit by the use of a 6-in. diameter pipe that was cut to length in the field. Large taper washers were used to plumb each pipe, which is secured to the roof by a standard rock bolt driven on the tunnel centerline. The resulting installation was therefore extremely economical. On the Branch main line, lightweight fabricated steel poles were found to be



FIGURE 5 Tumbler Ridge Branch Line: 50 kV, main-line simple catenary and feeder.

economical (see Figure 5). The cross arms used direct registration of the contact wire, thereby omitting the short registration arms customary on lines catering to higher speeds.

PROSPECTS

Because of the expectation of increased activity in railroad electrification, it is the turn of the manufacturers and the contractors to economize their supply and installation costs. Because the current range of catenary fittings manufactured in the United States has remained basically unchanged for the past 50 years, considerable opportunity exists to develop new designs by using new techniques and new materials. Similarly, the demonstration of custom-built rail-mounted equipment for track renewal is the springboard for catenary installers to develop sophisticated construction equipment for operation either on-track or off-track. Reduced pole counts, light poles, small foundations, improved component designs, and specialized equipment will

not only lower construction cost, but they will reduce the total work content, thereby freeing the track for traffic more quickly. As a result, earlier completion of projects will be possible, and the prime benefits of electrification--faster trains and more economical operation--will be available to the operators at an earlier date and at a lower cost.

REFERENCE

1. H.I. Hayes. Modern AC Traction--The Role of the Civil Engineer. Presented at the Concurrent Annual Conferences of the Road Masters and Maintenance of Way Association and the American Railway and Bridge Association, Chicago, Sept. 14-16, 1981.

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Discretionary Spending of Class II Railroads

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ABSTRACT

In this paper a statistical analysis of differences in expense levels of 30 Class II railroads for the period 1968 to 1977 is described. After controlling for the physical activity level with a regression model, the spending variations associated with revenue level were attributed to management strategy. A pattern of spending between years and between railroads is revealed in this study that supports the hypothesis that managers attempt to smooth income and cash flow.

Railroad cost functions have been analyzed quite successfully over the years. Costs of operation are viewed as functional to specifics of the plant, equipment, and traffic of a railroad. In this study the differences in spending attributable not to engineering or operating efficiency but to economic strategy of management are reviewed. The increasingly competitive environment of the 1980s places a premium on measuring hypotheses about how managers behave. Better understanding of how railroad operators use their discretion may help in anticipating their reactions to future changes in regulation, competition, or market opportunities. Theoretically, expenses are described as functional to volume (variable) or not functional to volume (fixed); in reality the level and timing of an expenditure is part of an economic strategy.

STUDY HYPOTHESIS

Although certain costs are economically unrelated to volume, cash expenditures are subject to management discretion. During lean years managers are more adamant about the need to cut spending, whereas they are more liberal in spending when funds are available for investments as well as profits. Likewise, managers with comparatively high revenue traffic will invest more in improvements and maintenance, whereas managers on tight budgets will curtail spending wherever they believe they can afford to. As shown in Figure 1, spending tends to be greater than economic cost when revenues are sufficient and less than cost when revenues are not sufficient for the normal level of income.

The discretionary spending behavior of railroad managers has two dimensions. As the business cycle progresses, firms adjust their spending to keep periodic income and cash flow near the level perceived as normal. This kind of spending variation is commonly referred to as income smoothing, and basically means spending extra revenues and economizing during revenue shortfalls. The other dimension of discretionary spending represents differences in spending between firms according to what funds are available. This latter variation describes the reaction of management to the revenue level their firms' traffic mix and location allow. Analysis of between-year and between-firm spending differences allows a fuller understanding of income smoothing and rate level accommodation by railroad managers.