



American Railway Engineering and
Maintenance-of-Way Association

CHAPTER 16

ECONOMICS OF RAILWAY ENGINEERING AND OPERATIONS¹

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¹ The material in this and other chapters in the AREMA *Manual for Railway Engineering* is published as recommended practice to railroads and others concerned with the engineering, design and construction of railroad fixed properties (except signals and communications), and allied services and facilities. For the purpose of this Manual, RECOMMENDED PRACTICE is defined as a material, device, design, plan, specification, principle or practice recommended to the railways for use as required, either exactly as presented or with such modifications as may be necessary or desirable to meet the needs of individual railways, but in either event, with a view to promoting efficiency and economy in the location, construction, operation or maintenance of railways. It is not intended to imply that other practices may not be equally acceptable.

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INTRODUCTION

The Chapters of the AREMA Manual are divided into numbered Parts, each comprised of related documents (specifications, recommended practices, plans, etc.). Individual Parts are divided into Sections by centered headings set in capital letters and identified by a Section number. These Sections are subdivided into Articles designated by numbered side headings.

Parts 12 through 15 of this Chapter formerly constituted Parts 1 through 4 of Chapter 11, which has been eliminated from the AREMA Manual.

Page Numbers – In the page numbering of the Manual (16-2-1, for example) the first numeral designates the Chapter number, the second denotes the Part number in the Chapter, and the third numeral designates the page number in the Part. Thus, 16-2-1 means Chapter 16, Part 2, page 1.

In the Glossary and References, the Part number is replaced by either a “G” for Glossary or “R” for References.

Document Dates – The bold type date (Document Date) at the beginning of each document (Part) applies to the document as a whole and designates the year in which revisions were last made somewhere in the document, unless an attached footnote indicates that the document was adopted, reapproved, or rewritten in that year.

Article Dates – Each Article shows the date (in parenthesis) of the last time that Article was modified.

Revision Marks – All current year revisions (changes and additions) which have been incorporated into the document are identified by a vertical line along the outside margin of the page, directly beside the modified information.

Proceedings Footnote – The Proceedings footnote on the first page of each document gives references to all Association action with respect to the document.

Annual Updates – New manuals, as well as revision sets, will be printed and issued yearly.





American Railway Engineering and
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Part 1

Railway Location¹

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¹ References, Vol. 71, 1970, p. 401. Adopted 1970.

SECTION 1.1 BASIC ECONOMIC CONSIDERATIONS

1.1.1 RELEVANCE OF LOCATION

- a. Although railway mileage has been shrinking, at least in the United States and Canada, opportunities for railway location still arise. There are several reasons which may make it necessary or desirable to relocate a segment of line or to build a new line or an extension.
- (1) Relocation of a segment of an existing line may be required for external reasons, i.e., because an outside party will acquire the land on which the segment is located, either through negotiation or by condemnation. In either case it is important that the railroad make a complete inventory of the property to be taken and its condition, as well as detailed records of the cost of the new line and any temporary or permanent change in operating cost caused by the relocation, before any work is undertaken. Salvageable material may be included in the acquisition or may be retained by the railway for use elsewhere. The railway may take the opportunity to include betterments, such as heavier rail, on the relocated line.
 - (2) New lines are built to reach new sources of traffic such as mines, power plants, manufacturing facilities, industrial parks or waste landfills.
 - (3) Relocation or realignment may be made for internal reasons. A relocated line may provide better profile or alignment, making possible worthwhile increases in trainload or speed, or making room for additional main track, reducing congestion. A relocation or extension may enable a railway to gain better access and provide better service to existing sources of traffic.
 - (4) In Europe and Japan new lines have been and are being built as very high speed passenger lines. Similar projects are in various stages of consideration or planning in the United States.
- b. When a relocation is made for external reasons, the other party can be expected or required to make the railway whole, to pay for a new line segment as good as the old or, if this is not feasible, to compensate the railway for the future increase in operating expenses (or, more rarely, loss of revenue). When the reason for a contemplated relocation, extension, or new line is to gain new business or to reduce operating expenses or improve service, the required capital expenditure must be evaluated in terms of the decrease in expenses or increase in revenue as discussed below in [Section 1.1.3](#) and [Section 1.1.4](#). In the case of high speed passenger lines or relocations for commuter service, probably to be built and frequently to be operated with public support, the revenue includes not only the passenger fares but also the estimated value of public benefits, such as reduced highway and airport congestion.

1.1.2 DEFINITION OF LOCATION

- a. A railway line is said to be located when its position is defined in relation to the generally accepted geodetic and geographic references of the area and at some stage staked out on the ground.
- b. The refinement of this definition depends upon the precision requirement of the designated level of planning, i.e., projected, reconnaissance, preliminary, final, or constructed.
- c. The line geometry is defined by the specified limits of its parameters, i.e.,
- ruling grade: the grade which limits the maximum weight of train which can be hauled by a given locomotive and which may not be the same as the maximum gradient if the latter is so short that an entire train is not on it at the same time or if its effect is reduced by momentum;
 - compensation for curvature: the reduction in grade on curves to offset curve resistance.
 - maximum rate of change in vertical direction;





- minimum tangent distance between points of vertical curve and between points of spiral curve;
- spiral formulas;
- and minimum clearances.

- d. Easy grades and curves and ample tangents and spirals make possible heavy trains, high speeds, and smooth train handling. For relocations or extensions of short or moderate length, train size or running times may be controlled by the characteristics of the rest of the line so that expenditures to permit heavier trains or higher speeds on the new segment are not justified. The achievement of easy grades and curves and ample tangents and spirals may be impeded by limitations on the maximum cut and fill having economic justification and the cost of bridges and tunnels. Other limiting factors are geotechnical varying from solid rock to unstable soils, liability to flooding, the preemption of land by public facilities such as highways, and the high cost of land. There are also environmental constraints such as avoidance or protection of wetlands and protecting residential areas from noise.
- e. Geographic factors are topography, streams, geotechnical features (stability and load-carrying capacity of earth and rock), current and prospective land use, environmental considerations (such as damage to animal habitats or noise in residential areas), and existing structures.
- f. Good railway line location is an economic choice of alternatives, weighing the capital cost of various possible lines against the revenues and expenses to be expected when these various possible lines are operated. The word, “revenue,” may be broadly interpreted. In the case of a facility built for a public purpose, such as a commuter line or a high speed passenger line, the benefits of not having to build highways, or reduced congestion and pollution, of time savings to the public, and of increased real property values are properly included. Even in the case of a private enterprise railway company, it is possible that improved transportation may enhance the value of some real estate owned by the company.
- g. The capital cost includes the costs of land, grading, structures, track, signal and communication facilities, avoidance of injury to the environment, and regulatory costs.
- h. Revenues include the revenue from traffic gained or retained by new or improved access to customers and by improved services. It is also possible that the improved transportation may enhance the value of some real estate owned by the railway. Expenses are generally the cost of train operation, including equipment maintenance and the costs of maintaining the line.
- i. In the weighing of capital cost against anticipated changes in revenues and expenses, allowance must be made for risk. Projects are not always completed on time and within budget. Geotechnical conditions may not be as favorable as expected; regulatory impediments may arise. Even more subject to risk are projections of revenues and expenses; business may not be as great as expected; competitors’ response to improved service may be more effective than anticipated. If volume of traffic is less than expected, operating expense savings will also be less. It may be that other factors can also limit operating savings. For example, reduction in the number of daily trains made possible by a lower ruling grade may not be achieved because service obligations dictate the running of frequent trains.

1.1.3 PRINCIPLES OF ECONOMIC DESIGN

- a. The principles of economic design have been summed up in four rules, stated by A. M. Wellington in his book titled “The Economic Theory of the Location of Railways.”
 - (1) “Regardless of how profitable a line promises to be, no expenditure over the absolute minimum is justifiable which is not of itself a profitable investment.”
 - (2) “Conversely, an increase of expenditure which is profitable of itself should always be made.”

- (3) “The exception to the rule immediately above is that no additional expenditure is wise which endangers completion of a project with the funds available.”
- (4) “Unless the traffic volume can be predicted quite exactly, it is often best to postpone any expenditure where that can be done without great loss.”
- b. These principles, published a century ago, are still valid today and apply to relocations and extensions as much as to new lines. These principles imply that a project should be, to the extent feasible, analyzed in terms of the absolute minimum required and of increments to that minimum. An increment should be included in the project only to the extent that it is itself profitable, i.e., that it confers an increase in benefits sufficient to justify its increase in capital cost. Since capital funds are limited, the most profitable increments should be included first, and no increment should be included which, by its capital needs, imperils the completion of the project with the funds available. The fourth principle, (d), may seem futile; when can we ever, “predict traffic volume quite exactly?” The principle simply means: build small and expand later when, and if, the anticipated traffic materializes.
- c. As an example of the fourth principle, a double track bridge is somewhat cheaper than two single track bridges, but if one single track bridge will suffice for several years until the traffic grows, the interest saved by postponing the expenditure will offset the greater cost of two single track bridges. If the traffic does not grow, the one single track bridge will continue to be enough. On the other hand, if reasonably likely growth in traffic justifies building a line with a low ruling grade, it would be wasteful to build a cheaper line with a higher ruling grade only to abandon it in a few years.
- d. Obviously, a quantitative evaluation of probabilities, a risk analysis, is required, and not just an intuitive judgment. One point to be considered in the risk analysis is the possibility that future expansion to provide capacity for possible growth in traffic may be costly or even impossible because, perhaps, land available now may, in the future, increase greatly in price or be taken for other uses.
- e. Location can contribute to increasing or retaining revenue through improved access to sources of traffic and through facilitating more competitive, i.e., more reliable and speedier service.
- f. The costs of train operation increase, first of all, with the number of trains required to carry the traffic and, hence, chiefly with ruling grade. Adding more locomotive units to a train can, to a considerable extent, compensate for heavy grades, but it is an expensive cure. The extent of savings from reducing the ruling grade depends on the volume of traffic. Increasing the tonnage rating from, say, 6,000 tons to 9,000 tons will save one train a day if the daily traffic is 18,000 tons, two trains a day if it is 36,000 tons, and so on.
- g. Operating costs are also affected by grades other than the ruling grade and by curvature. Curvature is especially burdensome where speed is required as is particularly the case with intermodal and passenger operations. To maintain competitive running times in spite of curvature requires, if it is possible at all, rapid deceleration and acceleration and perhaps higher speeds on more favorable sections of the route. The costs of maintaining the line increases with bridges required, length of line, and geotechnical conditions, as well as with curvature and grades and the speed and number of trains operated, i.e., with the volume of traffic.
- h. Because both capital requirements, especially for capacity, and revenues and expenses depend on volume of traffic, it is important that every effort be made to arrive at reliable estimates of future traffic and of the probability, and risk, of specified greater or lesser traffic volume. Risk analysis of the other factors, capital costs and operating and maintenance expenses must also be made.
- i. At least qualitative evaluation must be made of geotechnical risk, possible alternative design options, future environmental risk and regulatory risk. The future introduction of new technology should also be considered. New types of equipment may make grade reduction or curve reduction less important.
- j. Easy grades and curves and ample tangents and spirals make possible heavy trains, high speeds and smooth train handling. For relocations or extensions of short or moderate length, train size or running time may be





controlled by the characteristics of the rest of the line, so that expenditures to permit heavier trains or higher speeds on the new segment are not justified. The achievement of easy grades and curves and ample tangents and spirals may be impeded by limitations on the maximum cut and fill having economic justification, and the cost of bridges and tunnels. Other limiting factors are geotechnical, varying from solid rock to unstable soils; liability to flooding; the preemption of land by public facilities such as highways; legal restrictions on the acquisition or use of land; and the high cost of land. There are also environmental constraints, enforced by law or political realities or required as good public relations, such as avoidance or protection of wetlands and protecting residential areas from noise. Any other legal, regulatory, and political constraints must be taken into account. The avoidance or elimination of road crossings may be an important or even the principal consideration. Tax effects of investment and operation must be taken into account.

- k. The requirements for high-speed lines, such as the TGV in France, are quite different from those of conventional railroads. To permit high speeds, curves must be much more gentle. On the other hand, because the train must have a high power-to-weight ratio, and because of the great momentum at high speeds, grades, especially not-very-long grades, can be far steeper, and length of line is much more significant, than on conventional railroads.

1.1.4 INVESTMENT EVALUATION

- a. The following discussion is only a summary of the investment evaluation process. For more detail as well as discussion of the advantages and disadvantages of each method, see [Reference 1](#). The financial staffs of the larger railways should be experienced in the evaluation of capital projects.
- b. Estimated time of construction including land acquisition and the timing and amount of funds expended prior to the completion date, as well as the lag in the amount of cash recoverable from salvage of the abandonment, should be considered, and calculated.
 - (1) Proposed new lines, extensions, or relocations must be judged in the same way as other proposed capital expenditures, such as those for equipment or new technology.
 - (2) Relocations to improve service in order to attract or retain traffic or to reduce expenses can be compared with other capital expenditures for the same purposes, such as new, more efficient motive power and, of course, weighed against retaining the status quo.
 - (3) Strategic considerations, as for new lines or extensions into new territory, may be a primary reason for a project but are particularly difficult to quantify. New lines and extensions are evaluated in terms of the net earnings of the traffic they reach, giving weight, in some instances, to the possibility of competitive retaliation which may take away traffic or force rates down; it may be unwise to short-haul one's connections.
 - (4) Construction cost levels likely to be in effect during the time the project is being carried out and the costs of construction alternatives must be estimated. The cost of capital, interest on debt (which may well differ from the interest rate on equipment debt) and necessary return on equity must be taken into account. Allowance must be made for ad valorem taxes (or whatever tax method is actually used by the state in which the project is located), income taxes, and income tax deferrals.
 - (5) The availability of suitable computer programs makes financial calculation so quick and inexpensive that a reasonably sophisticated financial analysis can be made of every plausible alternative.
- c. There are a number of measures used in evaluating capital investments. Among them are: internal rate of return, widely used in the railroad industry; project payout period; net present value, to be compared with amount or present value of investment; profitability index; and benefit/cost ratio, widely used in government for public projects.

Internal rate of return is the discount rate which the railroad would have to apply to future cash flows in order to be indifferent between undertaking the project and not undertaking it.

$$\sum_{i=0}^n \frac{B_i - C_i - I_i}{(1 + r_d)^i} = 0$$

Project payout period is the number of years over which the sum of annual net benefits equals the investment or capital costs of the project.

$$\sum_{i=0}^n B_i - C_i = \sum_{i=0}^m I_i$$

Net present value is the present value of net benefits, to be compared with investment.

$$\sum_{i=0}^n \frac{B_i - C_i}{(1 + r)^i}$$

Profitability index is the ratio of net present value to present value of investment.

$$\frac{\sum_{i=0}^n \frac{B_i - C_i}{(1 + r)^i}}{\sum_{i=0}^m \frac{I_i}{(1 + r)^i}}$$

Benefit/cost ratio is the ratio of benefits to costs when both are reduced to present values.

$$\frac{\sum_{i=0}^n \frac{B_i}{(1 + r)^i}}{\sum_{i=0}^n \frac{C_i + I_i}{(1 + r)^i}}$$

In these expressions:

- i is year
- r_d is internal rate of return expressed as a decimal
- r is discount rate, expressed as a decimal, applied to future cash flows (either the railroad's cost of capital rate for fixed facilities or a higher "hurdle rate" set by management as a minimum required for new projects).
- n is the number of years in a project's life





- B_i is the total benefits in year i , including tax savings, if any, salvage values, and, in some cases, estimates of the cash equivalent of noncash benefits such as the enhancement of the value of land.
- C_i is the total cost in year i , including tax savings, if any, and, in some cases, estimates of the cash equivalent of noncash costs such as reduction of the value of land, excluding the capital expenditure for the project.
- I_i is the capital expenditure for the project in year i ; the investment in year i .
- m is the number of years to complete the project

- d. Investment evaluation is not as cut and dried as these precise formulas imply. All of the numbers, even the investment cost, the cost of construction, as well as the time required for construction, and the time required to realize benefits, including salvage, are estimates of future expenditures or receipts and their timing. Obviously the level of confidence in the result of the computation depends on the level of confidence in the various inputs. There are methods for quantifying the level of confidence in the result, but they depend on quantitative measure of the levels of confidence in the various inputs, measures which are themselves uncertain estimates.

1.1.5 BASIC PRINCIPLES OF LOCATION

The following brief points summarize the basic principles which should guide location projects.

- Management should provide or approve a clear statement of purpose and need for the new line, extension or relocation, including economic and strategic reasons.
- There should be recognition of the overall transportation system involved, of which this location is usually only a part. In particular, a relocated segment should not impose tonnage or clearance limitations which would adversely affect operations on other parts of the system. Conversely, there is no need to expend capital to permit higher tonnages or larger clearances if other line segments already limit them.
- The engineer in charge must recognize that his primary responsibility in planning is to develop a proposal which can be economically justified in accordance with criteria established by management (See [Section 1.1.3](#) and [Section 1.1.4](#)).
- The capacity requirements for a suitable period of years, based on estimates of the volume and classes of future traffic, must be estimated.
- New or changing business opportunities and requirements should be taken into account, as should other uncertainties in traffic forecasts.
- Line extensions to reach traffic sources may involve intermodal traffic. In such cases, the presumably higher cost of longer highway movement must be compared with the added rail investment needed to minimize mileage by highway and possibly with the added rail cost imposed by any resulting increase in ruling grade or other factors.
- The feasibility of proposed construction must be weighed, and construction's interference with operations must be allowed for and, to the extent practicable, minimized.
- The parameters of the line geometry best adapted to the terrain and to the economical performance of the service must be established.
- The standards of design and construction best adapted to the economical performance of the service must be established.

- j. A sufficient number of alternative solutions must be investigated.
- k. The final test is the investment evaluation.

1.1.6 TRAFFIC FORECASTS

- a. Locating a railway in effect constitutes designing a physical plant which can produce railroad transportation as economically as possible whose quality of service is commensurate with the nature of the traffic at hand.
- b. Almost all decisions regarding the design and location of a railway depend in some way upon the quantity and class of traffic it is to handle. A railway plant which is satisfactory for a given quantity and class of traffic may not be satisfactory for a different quantity or class of traffic. It is, therefore of the utmost importance that estimates of present and future traffic be as complete and accurate as possible. Where substantial uncertainties exist, separate economic analyses for different levels and classes of traffic may be necessary to assess the benefits or losses which would result from major changes in traffic conditions.
- c. A marketing analyst is a necessary member of a line location planning group.

SECTION 1.2 DESIGN CONSIDERATIONS

1.2.1 INITIAL CONSTRUCTION

- a. When a new line is projected in undeveloped territory which can be a source of only small traffic for a number of years but which can be expected to grow with the stimulus of a railroad, it may be advantageous to introduce extra distance, sharper curves, or steeper grades wherever these are so situated as to be capable of reduction at reasonable expense when justified by growth in traffic. Costs and difficulty in acquiring property for future improvements must be considered. This situation was not unusual in the days of railroad building in this country. It may arise in developing countries today but would be rare in the United States or Canada.
- b. The desirability of each interim construction depends upon whether the interest saved by deferring the construction of the final line will offset the cost of the cheaper work ultimately to be abandoned and the higher train operating costs during the interim. A review of existing, as well as a forecast of future, tax policy as related to capital improvements is essential to planning interim construction.

1.2.2 CUSTOMER SERVICE

- a. Since freight billing and car supply and control of train movements are now very much centralized, there is little occasion to provide for small stations. However, provision should be made for yard facilities at major traffic generating points. For passenger, commuter or high-speed inter-city lines, provision should be made for stations at potential traffic generating points.
- b. If nearby areas are suitable for industrial development, the line should be located and land should be obtained (or optioned) to preserve this potential.

1.2.3 COMMUNICATIONS FACILITIES REQUIRED

- a. For surveying and construction, communications facilities required will probably include two-way radio and some form of data transmission or telephone service between construction headquarters and the railroad's headquarters. Telephone service to the Public Switched Telephone Network (PSTN) will also be necessary to communicate off-line.





- b. Portable radio transceivers carried by survey party members will be most helpful, as well as keep them in contact with construction offices. At least one base radio station should be provided at the construction headquarters to provide contact with survey crews, as well as radio-equipped construction and survey vehicles.
- c. During the construction phase, there might well be need for data transmission, including facsimile between construction headquarters, field forces, suppliers and railroad headquarters.



1.2.4 MOTIVE POWER

- a. For short relocations and extensions, design should be adapted to the type of motive power (e.g., number of units, horsepower, four motor or six motor) used and to be used on the rest of the line. For longer segments, the optimum combination of line and locomotive characteristics can be chosen.
- b. High-speed passenger trains require much easier curvature than is acceptable on conventional railroads but, because of their high horsepower-to-weight ratio and the great momentum resulting from high speed, they can accept much steeper grades.



1.2.5 TERMINAL/SYSTEM OPERATIONS

- a. For new lines, adequate terminal facilities should be planned, but initially only the minimal portions built.
- b. For line relocations, the terminal problem is usually well outside the limits of the new construction. It usually consists of shifting the work load from one terminal to another. Labor problems tend to be the paramount consideration.
- c. Shifts in work load may be temporary or permanent. They may pose the risk of added labor cost but, if properly addressed, they may offer opportunity for improving efficiency or service.



1.2.6 RULING GRADES

- a. Definitions: The ruling grade is that segment of adverse grade which limits the tonnage a locomotive can haul over a line of railroad. It is not necessarily the maximum grade. Momentum grades and grades short enough to permit utilization of a locomotive's short-time rating may be steeper.
- b. Ruling grade is usually the most important consideration in freight line location (excepting only gaining access to traffic) because it determines maximum train size and thereby the number of trains, and hence crew and locomotive cost, required to handle a given traffic.
- c. Ruling grades should be designed uniformly over the entire distance between major traffic generators or train makeup and break-up points.
- d. If there is a possibility of substantial growth in traffic, and where it is feasible to do so, sections of ruling grade should be so located as to facilitate future reduction if growth warrants.

1.2.7 HELPER DISTRICTS

- a. Ideally, locomotives should be working at or near capacity over as much of their district as possible. Where a reasonable balance cannot be made between proposed ruling grades and the rest of the line, it may be best to concentrate adverse grades into one relatively short, steep section. This section can then be operated as a helper district with one or more helper locomotive units on each train.
- b. Helper grades should be such as to permit utilization of the full capacity of the helper and train locomotives on a full tonnage train as determined by the ruling grade on the remainder of the district.

- c. Helper service is less desirable for modern, high-speed freight operation because of the delays (and thus costs, as well as impairment of service) associated with cutting the additional engines in and out. These feature are especially significant where the length of train requires that helper engines be cut into the middle of a train. Scheduled fast freight trains should have a high enough ratio of horsepower to weight that they will generally operate at higher than “drag” speed. They may use helpers to maintain speed over the helper district, if the increased speed more than offsets the time lost cutting the helpers in and out.
- d. The advantages of helper grades must be weighed against the extra costs of helper crews and locomotives, not always operating from convenient terminals, and against the possible reduction in line capacity caused by the down-grade light engine movements.
- e. Also to be considered is the use of remote control or “slave” helper locomotives that are usually cut in about $\frac{1}{3}$ from the rear end of a train. The slave unit(s) are radio controlled from the lead locomotive. Such slave units may be kept in operation over an entire line to not only help the train over the steeper grades, but help sustain higher speeds and help improve train handling, especially train braking.

1.2.8 BALANCED PROFILES

- a. Usually the total tonnage moving over a line in one direction will not be the same as that moving in the opposite direction. If the ruling grade is the same in both directions, the result will be that locomotives (and thus crews) are not working to full capacity in the light tonnage direction.
- b. Where the extent of this traffic imbalance can be predicted with some confidence, it will be advantageous to spend more on construction cost toward reducing the ruling grade in the heavier tonnage direction than in the lighter. The ruling grades should be so balanced that the tractive effort required in each direction, and hence the number of trains, is the same. Note that in computing train resistance (and thus required tractive effort), it is necessary to specify a desired train speed.

1.2.9 MOMENTUM GRADES AND LOCOMOTIVE SHORT-TIME RATINGS

- a. Momentum grades may often be used to effect economy in construction costs without reducing train size or the over all operating efficiency of a line. Such grades should not be located at points where train stops or reduced speeds (below those required to operate the grade) are likely to be necessary. The number and character of these grades should, in any case, be such as to minimize the number and severity of train slack run-ins and run-outs.
- b. Momentum grades should not exceed that grade over which a locomotive loaded for the ruling grade could handle its train in two parts if stalled in the sag.
- c. The length of momentum grades should be such that the maximum speed of tonnage freight trains at the bottom of the sag will not exceed the speed limit for such trains; and such that the minimum speed at the top of the grade will not be less than the speed at which the motive power exerts its maximum tractive effort and in any case should not be less than, say, ten miles per hour to leave some margin.
- d. Short grades, even where momentum cannot be utilized, may exceed the ruling grade if they do not cause the locomotive to exceed its short-time rating.

1.2.10 COMPENSATION FOR CURVATURE

Ruling grades should be compensated for curvature so that the total train resistance on curves will not exceed that on tangent track.



1.2.11 GRADE THROUGH TUNNELS

- a. The grade through long tunnels should be kept as low as is economically practicable (except as noted below) in order to minimize the ventilation problem caused by locomotive exhaust gases and in order to increase the over all reliability of train operation. It is recommended that in general the grade through tunnels exceeding 1,000 feet in length should not exceed 75 percent of the ruling grade on the district. This reduced grade should preferably be carried some distance above and below the tunnel as well.
- b. A minimum grade sufficient to ensure proper drainage in tunnels should also be established. It is recommended that this be no less than 0.3 percent. A somewhat steeper grade may be in order in wet tunnels, where extremely cold weather can cause freezing of the drains.
- c. Summits and sags should be avoided in tunnels without provision for forced air ventilation. The seriousness of the ventilation problem will, in any case, depend upon the type of locomotives used, the number of locomotives in each train, the frequency of train movements and the natural air currents in the vicinity.

1.2.12 PASSING SIDINGS

1.2.12.1 General

Passing sidings should be located on flat grades or on minor summits in preference to sags or the sides of hills. If passing sidings must be located on ruling grades, the grade should be so compensated throughout the entire length of the siding as to permit tonnage trains to be started from a full stop. Where trains must be stopped to operate hand-throw switches at the entrance to and exit from the siding, such compensation should be carried a full train length beyond each end of the siding. Consideration should further be given to the compensation required on the turnout curves at each end of the siding.

1.2.12.2 Siding Length

- a. In determining the total length of passing sidings for freight trains, consideration should be given to the following: maximum length of train, entering speed, margin of stopping distance in siding, length of turnouts to clearance points, and required signal clearance. Highway crossings in sidings should be avoided.
- b. In general, the spacing between passing sidings (and thus the number of passing sidings on a district) should be determined on the basis of the traffic volume (number of trains per unit of time) and the resulting line capacity required, the average delay per train due to meets and passes, and the capital and maintenance costs of the sidings and their associated signaling.
- c. On single-track lines, in the interest of capacity, the time-spacing between adjacent passing sidings should be approximately equal over an entire district between traffic generation, traffic classification, or train make-up points. Time-spacing in this context is the time an average freight train in one direction requires to run between two sidings plus the time an average freight train in the other direction requires to run between the same two sidings.

1.2.12.3 Business or Set-Out Tracks

Where possible, turnouts to auxiliary tracks, such as customer's side tracks, which require switching by road crews should be located between switches on passing sidings.

1.2.13 SIGNAL DESIGN CONCERNS

- a. While signal system design is not, strictly speaking, a part of location, the locating engineer should, nevertheless, bear it in mind. As noted above, ruling grades should be adjusted to allow for stopping to open

and close switches entering and leaving sidings unless the planned signal (traffic control) system makes such stops unnecessary.

The following should be considered as regards train movement control:

- Automatic block signaling with movement orders by voice or digital radio.
 - Centralized traffic control.
 - Cab signals with or without speed control.
 - No wayside signals, but movement orders using voice or digital radio. With digital radio, the locomotive crew can receive movement orders in printed form on printers or computer monitors.
- b. If, as is common, equipment defect detectors are to be installed, thought should be given to locating set-out tracks.

1.2.14 ENVIRONMENTAL AND PUBLIC POLICY CONCERNS

- a. The locating engineer must consider the effects of the environment on the railroad and the effects of the railroad on the environment.
- b. Effort should be made to avoid unstable soils and areas subject to landslides or floods. There may be instances in which land should be avoided because of chemical or radioactive contamination.
- c. The locating engineer should be aware of environmental restrictions, such as the statutory protection of wetlands. He should try to forestall complaints of “noise pollution” by keeping some distance away from settled residential areas although this is often impossible. He should give consideration, even at the cost of extra earthwork (preferably fill rather than cut, to avoid drainage problems), to eliminating highway crossings at grade.
- d. Major considerations are the price of land, and governmental land use planning and restrictions, including zoning.

1.2.15 COMMUNICATIONS FACILITIES

- a. The length of a new line or a relocation will affect the communications facilities required. If such a length is 30 miles or less, for example, existing radio base stations or addition of only one or two more radio base stations might well provide the communications coverage required.
- b. Longer new lines or relocations several miles from an existing line might well require new radio base stations.
- c. On any such project, one should consider using existing communications facilities if sufficient coverage can be obtained. Existing base station sites such as housings, power supplies, and antenna towers might be used, adding only radio transmitter-receivers and antennas.

1.2.15.1 Surveys

- a. In making preliminary and final route surveys, communications can be helpful in surveying, mapping and coordination of all personnel involved. Basic two-way voice radio will be required. To provide coverage over a wide area, it might be helpful to use a portable base station to support vehicle and portable units carried by people in the working area. Digital radio might be used in the surveying process to record data and have it sent to a central office for recording and making maps and line plots, etc.



- b. Other surveying techniques use radar profiling, and global positioning satellites, as well as aerial photography.



1.2.15.2 Construction



- a. Two-way radio for voice and data transmission will be required to provide communications between construction crews and project headquarters. A base station will probably be required at the headquarters, and probably more than one frequency will be required to handle the communications load. For example, one frequency might be used between headquarters and the field, and another frequency used by field personnel to communicate with each other.
- b. If contractors are used on the project, they might have their own radio system so that there might be two such systems, one used by the railroad and one by the contractor. Coordination of the two would be essential to avoid any interference.



1.2.15.3 Operations and Maintenance



- a. For operations and maintenance, permanent base radio stations will be required. Also, connections will have to be made to tie the new line's communications facilities into the railroad's existing communications facilities. For example, if the railroad is using dispatcher-controlled radio base stations on the mainline, it may well wish to provide such service on the new line.
- b. If the new line serves customers, additional communications facilities may be required to handle voice or digital communications between the customer and the railroad's customer service center.



- c. Also on the operational side, if the railroad has a work-order system in service, it probably would be expanded to include the new line, hence digital radio base stations would have to be installed to provide this coverage along the new line.
- d. If the new line is a major traffic generator or a relocation of a major line, volume communications facilities may be required, such as fiber-optic cable or microwave radio, in addition to any two-radio required.
- e. Also, if the new line connects two major mainlines of the railroad or major urban areas, some of the cost of the new line might be offset by leasing right-of-way to a commercial communications company for a fiber optic-cable system. In the same vein, electric utility companies might wish to lease right-of-way space for a power transmission line.

1.2.15.4 Other Operating Control Facilities

- a. With automatic equipment identification now in service on many railroads and mandatory tagging of all freight cars operating in interchange, AEI scanners to read freight car and locomotive tags may be desirable. If the new line branches off a mainline, it may be helpful if an AEI scanner were positioned to scan trains entering and leaving the new line. Again, communications would be required to connect the AEI scanners into the existing communications facilities.
- b. Also, the railroad might well desire to install dragging equipment detectors and hotbox detectors on the new line. Here again radio transmitters would be installed at detector sites to provide detector response messages to crews of passing trains. (See [Part 5, Economics and Location of Defect Detector Systems](#).)
- c. If the railroad wishes to operate trains over 50 miles per hour, a block signal system shall be installed, as required by the Federal Railroad Administration. Thus signaling and communications facilities will be required.

SECTION 1.3 CHOICE OF DESIGN AND ALIGNMENT

- a. For a short extension, such as a spur to serve a nearby industry, or a short relocation, such as easing a curve, the detailed study discussed below is not practical, although effort should be made to confirm that the net revenue from the industry's traffic or the saving in time and expense and the reduction in hazard resulting from easing the curve justifies the investment.
- b. Before choosing an alignment of a new line or an extension or relocation of any substantial length, the general area where a route is desired should be examined. It is quite likely that two or more possible alignments, differing to a greater or lesser degree, can be laid out in the area. It is usually wise to examine more than one possible alignment in some detail, following the basic principles outlined in [Section 1.1](#), determining the elements of design described in [Section 1.2](#), and making careful estimates of construction costs. These estimates should be weighed against the estimated revenues and operating and maintenance expenses using traffic projections as described in [Article 1.1.6](#) and investment evaluations as described in [Article 1.1.4](#). In determining the elements of design for a line it will probably be necessary to make repeated changes in detail, weighing added investment in grade reduction, for example, against added net benefits in accordance with the principles stated in [Article 1.1.3](#). The competitive value of time saving in retaining or gaining traffic should not be overlooked.
- c. This examination of alternatives is particularly important when risks, or uncertainties, are high. In such case, it will be necessary to weigh probabilities. Is the probability of attaining the high estimate of traffic sufficient to justify the added cost of a lower ruling grade?
- d. In planning alignments it is important to give weight to environmental factors and to regulatory, political, and public relations considerations (See [Article 1.2.14](#)). The railroad is subject to federal, state, county, and municipal regulation and can be aided or injured by public and government opinion.
- e. In estimating investment, benefits, and costs, the effects of taxation must be given due weight as discussed in [Article 1.1.4](#).
- f. For a large project, design quality will be optimized if specialists in various functions of the railroad, including marketing and operations planning, contribute their expertise.



1.3.1 TRAFFIC AND OPERATING FACTORS

- a. Estimates of the volume and nature of traffic underlie all the computations of revenue, of the number of trains per day, and of operating and maintenance expenses. In the case of a long-term contract, such as for transporting coal to a power plant, the traffic estimate can be quite precise, but in many instances a traffic projection is subject to a wide range of error. In such a case, one can work from high and low estimates or simply recognize the uncertainty and not go to too much effort and expense in seeking fictitious precision in estimates of operating and maintenance costs.
- b. Service requirements should be forecast and the location designed to meet them, e.g., by providing for train speed or frequency.

1.3.1.1 Effect of Ruling Grade

From estimates of the volume and nature of traffic and the determination of the ruling grade, the average number of daily trains of each type (heavy unit trains, intermodal, general freight, local freight, etc.) can be calculated, giving weight to any expected seasonality. These calculations in turn make it possible to estimate with some confidence the level of investment justified to reduce the ruling grade.

1.3.1.2 Projected Train Performance (Modeling)

- a. Train performance computer programs take into account train characteristics, such as horsepower per ton, general speed restrictions, weight, and length; and line characteristics, such as grade, curvature, local speed restrictions, and distance; in order to compute speed at every point on the line, elapsed time, and fuel consumption.
- b. There are also computer dispatching algorithms which can be used to calculate train interference, delay, and congestion; with such a program, siding spacing and location can be evaluated.

1.3.2 CAUSES OF EXPENSES

- a. From the outputs of these computer programs, the locating engineer can ascertain the effects of the various line characteristics on transportation and equipment maintenance expenses. Crew wages are generally proportional to train-miles, but specific labor agreements should be checked. Locomotive maintenance is in part proportional to the number of locomotives required and in part to fuel consumption. The Surface Transportation Board (STB) has a computer program, Uniform Railroad Costing System (URCS), which develops such unit costs, although the individual railroad may well have better, more specific data. Car maintenance cost is similarly divided between car-mile cost and car-day cost. Foreign car cost is proportional to car time and mileage, private line car cost to car-miles.
- b. The expense of maintenance of way is in part related to miles of route and in part to gross-ton-miles, a traffic-based factor. It is also related to subgrade conditions, curvature, and grade. The URCS develops estimates of maintenance of way (M of W) and other costs although individual railroads probably have their own much better M of W budgeting programs. Since replacements of newly laid rail and ties will become necessary only years in the future, cash flow projections are desirable.

1.3.3 EFFECTS OF LINE CHARACTERISTICS

- a. Ruling grade determines the maximum weight of train and hence the number of trains, and their engines and crews, required to move a projected volume of traffic. While the diesel-electric locomotive with its high tractive force and multiple unit (m.u.) capability has greatly increased train size on grades, the fact remains that ruling grades still limit train weight.
- b. Grades other than ruling grades, rise and fall, do not limit train weight but impose the costs related to fuel consumption. To the extent that braking is not needed on fairly short descending grades, the kinetic energy gained is used in ascending out of the sag, and there is virtually no added fuel consumption. If a descending grade is long enough and steep enough to require braking, energy and fuel are lost (exception: on some electrified railroads, regenerative braking can return energy to the power system). An undulating profile, however, makes train handling more difficult and generates slack action, causing shocks to cars and lading and occasional break-in-twos.
- c. Length of line (distance) affects crew-miles, locomotive-miles (and fuel consumption), and car-miles as well as maintenance of way expenses.
- d. Curvature increases rail and wheel wear and, if uncompensated, increases fuel consumption. Rail wear on curves can be ascertained from the railroad's experience. Wheel wear may be estimated to be proportional to rail wear. Line and surface are somewhat more expensive to maintain on curves.

1.3.4 HIGHWAY-RAIL GRADE CROSSINGS

- a. While ideally, it is desirable not to have any highway-rail crossings at grade in newly constructed lines, often circumstances will make them necessary.
- b. It should be noted that the railroad will have to discuss such crossings with the road authority having jurisdiction, which includes the state highway or transportation department.

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American Railway Engineering and
Maintenance-of-Way Association



Part 2

Train Performance¹

— 2009 —

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¹ References, Vol. 71, 1970, p. 412; Vol. 93, 1992, p. 129.

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SECTION 2.1 RESISTANCE TO MOVEMENT

2.1.1 LEVEL TANGENT TRACK (1992)

- a. A railway vehicle moving upon level, tangent track, in still air and at a constant speed encounters certain resistances that must be overcome by the tractive effort of the locomotive.
- b. These resistances include:
 - (1) *Rolling friction between wheel and rail.* This can be considered a constant for a given quality of track.
 - (2) *Bearing resistance.* This varies with the weight on each axle and, at low speed, the type, design and lubrication of the bearing.
 - (3) *Train dynamic losses.* These include flange effects which are associated with lateral motion and the resulting friction and impact of the wheel flanges against the gage side of the rail. They vary with speed, rail alignment, track quality, the surface condition of the rail under load, the horizontal contour of the railhead, contour and condition of the wheel tread, and the tracking effect of the trucks. Also there are miscellaneous losses due to sway, concussion, buffing and slack-action.
 - (4) *Air resistance,* which varies directly with the cross-sectional area of the vehicle, its length and shape, and the square of its speed. It is also influenced by zones of turbulence related to shape.

- c. Various tests made over the years have shown that the resistance to train movement can be determined using an empirical expression of the following form:

$$R = A + BV + CDV^2$$

where:

R = train resistance in lb

A = rolling resistance component independent of train speed

B = coefficient used to define train resistance dependent on train speed

C = streamlining coefficient used to define train resistance dependent on the square of the train speed

D = aerodynamic coefficient or polynomial function used to further define train resistance, often combined with C

V = train speed in mph

- d. The predominate but not exclusive contributors to the various coefficients are shown in [Table 16-2-1](#).

Table 16-2-1. Coefficient Contributors

A	B	C and D
Journal resistance	Flange friction	Head-end wind pressure
Rolling resistance	Flange impact	Skin friction on the side of the train
Track resistance	Rolling resistance wheel/rail	Rear drag
	Wave action of the rail	Turbulence between cars
		Yaw angle of wind tunnels

2.1.2 DAVIS FORMULA – HISTORIC DEVELOPMENT (1992)

- a. In 1926, W. J. Davis ([Reference 21](#)) proposed an empirical formula for computing “Tractive Resistance of Electric Locomotives and Cars” moving on straight and level track. His proposed values for the coefficients A, B and CD shown in [Table 16-2-1](#) were as follows:

$$A = 1.3 + \frac{29}{W}$$

B = 0.03 for locomotives or 0.045 for freight cars, and

$$CD = \frac{Ca}{WN}$$

where:

R = Train resistance in lb/ton

W = Axle weight in tons per axle of locomotive or car

N = Number of axles

a = The cross-sectional area of the locomotive or car in square feet

C = The streamlining coefficient

C was given various values, e.g. 0.0024 for lead locomotives or 0.0005 for trailing locomotives and freight cars.

The equation which Davis proposed thus became (for freight cars):

$$R = 1.3 + \frac{29}{W} + 0.045V + \frac{0.0005aV^2}{WN}$$

- b. The original Davis formula has given satisfactory results for older equipment with journal bearings within a speed range between 5 and 40 mph. Tuthill ([Reference 82](#)) and Totten ([Reference 81](#)) had adjusted this formula for higher speeds. However, roller bearings, increased dimensions and heavier loading of freight cars, the much higher operating speeds of freight trains, and changes in the track structure have made it desirable to modify the constants in the Davis equation.
- c. Tests in the 1940's and 1950's showed improved results using the following modified Davis Formula ([Reference 37](#)):

$$R = 0.6 + \frac{20}{W} + 0.01V + \frac{KV^2}{WN}$$

where:

R = resistance in lb/ton
 W = weight per axle in tons
 N = number of axles
 V = speed in mph
 K = combined air resistance coefficient: 0.076
 for conventional equipment
 0.16 for piggyback
 0.0935 for containers

2.1.3 RECENT DEVELOPMENTS (1992)

- a. The original train resistance formula has been retained as to form, but over the years different coefficients have been developed to reflect changes such as higher speeds, more modern equipment, and today's track and truck designs.
- b. The 1990 Canadian National version of the train resistance formula ([Reference 16](#)) is presented below. When used with the coefficients shown (many of which have been developed in dynamometer car tests), the formula has given reliable results in train performance calculator programs or similar applications.

$$R_r = 1.5 + \frac{18N}{W} + 0.03V + \frac{CaV^2}{10000W}$$

where:

R_r = the rolling resistance of vehicle in lb/ton
 N = Number of axles
 W = Total weight in tons of locomotive or car
 V = Velocity of train in mph
 C = The Canadian National streamlining coefficient, and
 a = The cross-sectional area of the locomotive or car in square feet

- c. [Table 16-2-2](#) shows the range of values for the C coefficient for various kinds of equipment. Note that these values for C are scaled for use with the Canadian National formula only.



Table 16-2-2. Values of C Coefficient For Use with Canadian National Train Resistance Formula Only
(Reference 14)

Degree of Streamlining	Equipment	C Coefficient	
		Leading Equipment	Trailing Equipment
Nil 1	Open auto transporter	–	12.3
Nil 2	Freight locomotive	24.0	5.5
	Mixed consist of freight cars	–	5.0
Low 3	RDC	19.0	4.0
Low 4	Conventional passenger including locomotive	19.0	3.5
Med 5		14.0	3.0
Med 6		10.0	2.6
High 7	High speed passenger	7.6	2.3
High 8	Maximum possible streamlining	7.0	2.0



- d. When certain types of cars predominate in a train, more accurate resistance values for such a train can be obtained by using C coefficients from [Table 16-2-3](#). The table shows in more detail recommended Canadian National values for C and cross-sectional areas for the various equipment types.

Table 16-2-3. Values of C Coefficient and Areas for Freight and Passenger Equipment For Use with Canadian National Train Resistance Formula Only

Table 16-2-4. (Reference 15)

Type of Equipment	C Coefficient	Area (Square Feet)
Box Car	4.9	140
Bulkhead Flat (loaded)	5.3	140
Bulkhead Flat (empty)	12.0	140
Coal Gondola (loaded)	4.2	105
Coal Gondola (empty)	12.0	105
Covered Hopper	7.1	125
Tank Car	5.5	95
Standard Flat Car (without trailers)	5.0	25
Standard Flat Car (with trailers)	5.0	125
Caboose	5.5	145
Conventional Passenger Coach	3.5	130
Modern Lightweight Passenger Equipment	2.0	110
Leading Freight Locomotive	24.0	160
Multi-level Auto Transporter (open)	12.3	150
Multi-level Auto Transporter (closed)	7.1	170

- e. It will be noted that the C coefficients for empty gondolas and empty bulkhead flats are much larger than those for loaded gondolas and loaded bulkhead flats. This is due to the air swirling inside the empty car and the resulting turbulence.
- f. Through 1988, the Association of American Railroads produced a series of reports as part of its continuing energy program. These reports developed train resistances based upon the original Davis equation, but with a number of changes in the coefficients. Some of these changes include:
- (1) AAR tests on Class 3 or better track indicated a negligible value for the “B” term, which was dropped.
 - (2) Modern roller bearings have a resistance of 16-18 lb/axle, which is consistent with the 20 lb/axle used in the modified Davis Formula. These factors change the original Davis formula to:

$$R = 1.3 + \frac{18}{W} + \frac{C_{av}^2}{WN}$$

- (3) The speed-independent rolling resistance term (1.3) can vary from 2.13 lb/ton (loaded car) and 1.77 lb/ton (empty car) without wheel/rail lubrication, down to 0.8 lb/ton to 0.7 lb/ton with lubrication for three-piece trucks, and from 1.35 lb/ton (loaded car) to 0.91 lb/ton (empty car) for radial, frame braced, and primary aligned track designs.



- (4) Attributing the third term to aerodynamic resistance, the “C” term can be defined as follows:

$$R_{\text{aero}} = CV^2 = 0.5\rho(CDa)V^2$$

ρ is air density, which is dependent on air pressure and temperature. The (CDa) term is the drag area of the train (drag coefficient), which is determined by summing the drag areas for all cars in the consist. The Aerodynamic Subroutine of the AAR Train Energy Model version 2.0 expresses the “C” term as a seventh order polynomial function of crosswind yaw angle for each car, and then sums over all cars. Thus the drag areas of different trains will vary considerably, depending on car design, car spacing, wind yaw angle, and train make-up. Test data used to develop this model are available in AAR Report R-685 ([Reference 29](#)).

- g. Version 2.0 of the AAR Train Energy Model (TEM) incorporates this train resistance subroutine and data. This model permits simulation of train handling and includes fuel consumption, travel time, and speed profile as model output. To run the AAR TEM, the user does not need to gather resistance information.

2.1.4 STARTING RESISTANCE (1992)

- The resistance of journal bearings is much higher at starting than when the vehicle is in motion. Depending upon the weight per axle and the temperature of the bearings, which is in turn a function of both the ambient temperature and the length of time the equipment has been stopped, starting resistance may be as high as 35 lb/ton below 30 degrees F. An average for light and heavy cars of 25 lb/ton at starting is a conservative assumption for above-freezing temperatures.
- The starting resistance of roller bearings is essentially the same as when they are in motion. In general, a resistance value of 5 lb/ton (or less) should be satisfactory for roller-bearing equipment at above-freezing temperatures.

2.1.5 CURVE RESISTANCE AND RADIAL TRUCKS (1992)

- The additional train resistance due to curvature amounts to about 0.8 lb/ton per degree of curvature for three-piece trucks without wheel/rail lubrication. To put it another way, curve resistance can be said to be the equivalent of a grade of 0.04% per degree. For other than standard gage track the following relationship applies ([Reference 13](#)):

$$R_c = 0.17 (\text{gage})$$

where:

$$R_c = \text{Curve resistance in lb/ton per degree of curvature}$$

$$\text{gage} = \text{gage in feet}$$

- Primary suspension trucks (radial or self-steering, and primary aligned trucks) have less curve resistance. Experience with rail lubricators on curves has shown that their use can be expected to reduce curve resistance for three-piece trucks by as much as 45 to 50%. Tests have shown that they will practically eliminate curve resistance on curves of up to 9 degrees. Above 9 degrees, curve resistance is reduced by approximately 7 lb/ton ([Reference 1](#)). Some benefit in the form of reduced curve resistance can be obtained from the use of rigid-frame or cross-braced trucks, and tighter tolerances to improve three-piece truck alignment may also reduce resistance. Hence, if curve compensation is being considered, the amount of compensation should be proportionally reduced for locations where wayside rail lubrication will be provided or improved trucks will be used.

2.1.6 GRADE RESISTANCE (1992)

The additional resistance encountered on ascending gradients is equal to 20 lb/ton per percent of grade, and must be added to the other train resistances ([Reference 37](#)).

2.1.7 WIND RESISTANCE (1992)

Though on most lines trains do not move in a constant direction with respect to winds, the possible effect of winds on train resistance should not be ignored. The additional resistance due to head-winds can be accounted for by adding the average wind velocity to the train speed in computing air resistance. Wind-tunnel tests show that side winds at different yaw angles can increase train resistance significantly. The AAR Train Energy Model version 2.0 calculates the aerodynamic resistance “C” term as a seventh order polynomial function of crosswind yaw angle. Material on wind resistance will be found in AAR Report R-685 ([Reference 29](#)) and other references listed in References.

2.1.8 TUNNELS (1992)

Tunnels can increase the train resistance considerably. Factors which affect tunnel resistance are train length, tunnel length, the ratio of the cross-sectional area of the train to the cross-sectional area of the tunnel, and tunnel roughness ([Reference 62](#)). [Table 16-2-4](#) shows Canadian National C values for typical tunnel situations.

- a. In [Table 16-2-4](#) “q” represents the ratio of the cross-sectional area of the train to the cross-sectional area of the tunnel. The freight coefficients are for average mixed consists. If the values provided in [Table 16-2-4](#) are lower than those given in [Table 16-2-3](#), the values for the tunnel coefficients should be adjusted upward to take into account the combined effect of high open air resistance and tunnel influence.

Table 16-2-4. Typical Values of C Coefficient in Tunnels For Use with Canadian National Train Resistance Formula Only
([Reference 16](#))

Tunnel Length (Feet)	Train Type	q = 0.40	q = 0.65
2000	Passenger	4.0	6.0
5000	Passenger	6.3	12.0
2000	Freight	8.0	12.3
5000	Freight	12.6	24.0

2.1.9 RAIL LUBRICATION (1992)

- a. Experience with wayside rail lubricators on curves has shown that their use can reduce curve resistance by as much as 45 to 50%, permitting reduced curve compensation.
- b. Various tests have indicated large savings are available by using onboard flange lubrication. Benefits are obtained on tangent as well as curved track and are additional to benefits derived from wayside rail lubrication. Reductions averaging 0.8 lb/ton have been obtained for loaded cars on curves using this technique ([Reference 64](#)).
- c. A study by MIT found that track lubrication cut energy losses by roughly 25% over most of the operating speed range. The use of radial trucks gave results comparable to track lubrication, except that stability was increased (and losses decreased) at higher speeds on good track. Suspension losses increased for conventional trucks in lubricated curves over that found in dry curves, even though the total resistance was greatly reduced. On class 5 curves, the improvement due to lubrication for curves from 2 to 5 degrees averaged 35% for the AAR wheel ([Reference 5](#)).



2.1.10 TRACK QUALITY, TRACK MODULUS, AND CONCRETE TIES (1992)



- a. Higher track quality can reduce train resistance by reducing suspension losses and power losses in the wheel/rail contact area. MIT studies concluded that the level of track roughness has a considerable impact on dynamic resistance at low and moderate speeds on tangent track. On good track at high speeds, the losses are dominated by hunting, and roughness is less important. Curving resistance is less affected by track roughness, for the leading outer wheels are in flange contact beyond 2 or 3 degrees of curvature; on tangent track, roughness increases resistance by bringing the flanges into contact ([Reference 5](#)). Tests have shown that an increase in track quality from FRA class 4 to class 6 reduced rolling resistance by 0.3 lb/ton at 20 mph to 0.5 lb/ton at 60 mph on tangent track for cars with a gross weight of 104 tons. This increase in track quality reduced rolling resistance on curves of up to 2 degrees by 0.4 lb/ton for the same cars. Beyond 2 degrees little improvement was observed ([Reference 6](#)).
- b. Track quality can be improved by using concrete ties instead of wood ties, using continuous welded rail instead of jointed rail, increasing the depth of the ballast section, increasing rail cross-section, and in other ways strengthening the track structure.
- c. Studies have shown that train resistance can be substantially reduced when trains are operated over track with concrete ties rather than wood ties. The reduction is due to the higher track modulus which implies stiffer track. There results a decrease in energy lost in the car suspension and in the roadbed. The installation of concrete ties in place of wood ties under 132 lb rail, for example, can decrease rolling resistance by approximately 0.5 lb/ton for cars with a gross weight of 130 tons. For empty cars (25 tons), the reduction under the same circumstances is approximately 0.1 lb/ton ([Reference 25](#)).

2.1.11 ARTICULATED CARS (1992)

- a. Articulated cars can be used to reduce train resistance, due to fewer axles. Examples are found in high-speed passenger trains and multiple-unit intermodal cars.
- b. For example, to calculate train resistance for a high-speed passenger train consisting of “n” vehicles, where the C coefficient for leading vehicles is C_{ld} and the C coefficient for trailing vehicles is C_{tr} , the overall C coefficient for such a combination will be:

$$C_{\text{combined}} = \frac{C_{ld} + (n - 1)C_{tr}}{n}$$

- c. Note that lower-case n above refers to the number of vehicles. As usual, upper-case N in the train resistance formula would represent the number of axles in the combination.

2.1.12 FOUR-WHEEL CARS (1992)

Four-wheel (two axle) cars can contribute to reduced train resistance due to fewer axles and reduced weight. The use of two-axle cars allows N to be set at 2, rather than 4 as is normally the case, in the train resistance formula. Curve resistance can be increased due to a longer rigid wheelbase, however.

2.1.13 EMPTY GONDOLA, HOPPER AND BULKHEAD FLAT CARS (1992)

As noted in the [Table 16-2-3](#) which gives C coefficients for various car types, empty gondolas have a much higher C coefficient than loaded gondolas. This is due to the open space within the empty cars which can trap a good deal of air and cause substantial turbulence. This increase can be of the order of 150% to 200% ([Reference 24](#)). The same effect applies in the case of empty open top hopper cars but to a reduced degree.

2.1.14 HIGH-SPEED PASSENGER TRAINS (1992)

Streamlining can be used to lower the C coefficient in the train resistance formula. With a high degree of streamlining, the C coefficient for leading vehicles can be reduced by as much as 60% and that for trailing vehicles can be reduced by 33% compared with the coefficients for conventional passenger trains of the style built during the 1950's ([Reference 15](#)).

2.1.15 OTHER FACTORS (1992)

Air conditioning, atmospheric temperature, equipment weight, locomotive contour, passenger train contour, rail support, rail weight and condition, speed on curves, track conditions, and forces due to side winds are other factors which can affect train resistance.

SECTION 2.2 TRAIN PERFORMANCE CALCULATIONS

2.2.1 SPEED-TIME-DISTANCE RELATIONS (1992) ([Reference 75](#))

- a. The procedure required to determine the speed, time and distance relations for a given type of equipment moving over a given route can best be described by means of a numerical example. After considering classical step-by-step method, some suggestions will be made concerning the possible use of a computer to reduce the labor and shorten the time required for the calculations. The following information is required before calculations can begin.
 - (1) The speed-tractive effort curve for the locomotive to be employed.
 - (2) The train resistance curve (level, tangent track) for the rolling stock making up the train.
 - (3) Significant data concerning the track profile, such as the location and degree of curves, the location of grades, the location of stations and places where slow orders prevail.
- b. Let it be assumed that the locomotive is electric, of the rectifier type, weighing 400,000 lb, all on drivers. The train will be made up of fifty 60-ton freight cars. [Figure 16-2-1](#) shows the speed-tractive effort curve for the locomotive and the assumed resistance curve for a 60-ton car. Assume also that the train is to be started and brought up to balancing speed on level, tangent track. Convenient velocity increments will be chosen, say 10 mph initially, changing to smaller increments as balancing speed is approached. Also assume that the pounds-per-ton resistance of the locomotive is the same as the freight car. For each speed increment, the calculations are carried forward in the following order:
 - (1) For the average value of the velocity increment, dV , determine from the resistance curve the corresponding pounds per ton, and multiply by the train tonnage, including the locomotive.
 - (2) Obtain the pounds of tractive effort, T_a , available for producing acceleration by subtracting the value obtained in [paragraph \(1\)](#) from the total tractive effort developed by the locomotive.
 - (3) Because it takes about 100 lb to accelerate a mass of 1 ton at the rate of 1 mph per second, multiply the total train tonnage by 100 and divide the value obtained in [paragraph \(2\)](#) by the product, i.e. the total train tonnage times 100, obtaining the acceleration, dA .
 - (4) The time (seconds) required to complete the assumed velocity increment is found by dividing the velocity increment by the acceleration obtained in [paragraph \(3\)](#).

$$dt = dV \div dA$$

- (5) The distance (feet) travelled during this increment is then determined.



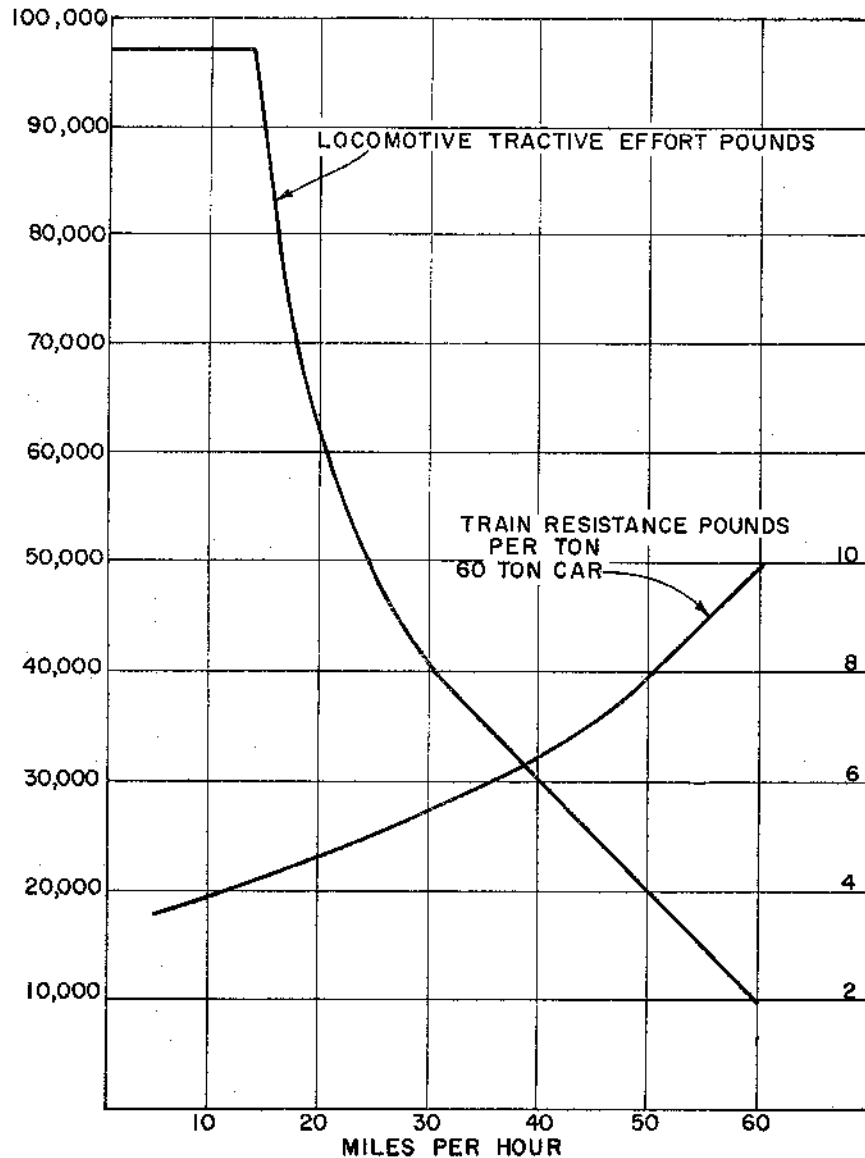


Figure 16-2-1. Speed-Tractive Effort Curve for the Locomotive and the Assumed Resistance Curve for a 60-ton Car

$$dS = 1.47(V_{av})(dt)$$

- c. Table 16-2-5 shows the calculations carried through four velocity increments. If this procedure is continued up to the balancing speed (which will be about 46 mph on level, tangent track), the total time and the total distance covered will be obtained. However, let it be assumed that at the end of the 4th velocity increment, when the speed has reached 35 mph and the train is 8,926 feet from the starting point, a long, uniform grade of 0.5% is encountered. This adds 32,000 lb to the train resistance and brings the total resistance up to a value greater than the locomotive tractive effort, so that the speed will begin to reduce. The next line in the table shows how this is handled. A small negative speed increment is assumed, in this case, 2 mph, and the corresponding values of accelerating force, dA , dt , and dS are computed. It will be found that the balancing speed on this grade will become about 25 mph.
- d. The resistive effects of curves can be handled in a similar manner.

Table 16-2-5. Train Performance Calculations

dV	V _{av}	T _a	dA	dt	t	dS	S
10	5	85,800	0.268	37	37	272	272
10	15	70,000	0.219	46	83	1,014	1,286
10	25	32,000	0.100	100	183	3,675	4,961
5	32.5	19,300	0.060	83	266	3,965	8,926
-2	34	-14,900	-0.0465	43	309	2,149	11,075

- e. Either of the two basic types of computers (analog and digital) may be employed in the study of train performance over a given route. One form of analog computer used for this purpose employs three or more curve-drawing instruments, which are basically potentiometers. These are designed to show distance, velocity, acceleration, power consumption, etc., as functions of time. The basic track data such as location of grades, curves, stations, speed restrictive zones, are first carefully inserted on the distance-time chart. Data related to the equipment to be used, such as train resistance values, locomotive tractive effort, etc., are fed to other curve-drawing instruments, and the operator adjusts the voltage inputs to the various instruments as the charts are advanced by their respective drive motors. (See [Article 2.2.3](#) for Digital Computer Method.)

2.2.2 VELOCITY PROFILES (1970) ([Reference 3](#), [36](#), and [74](#))

- a. Another method of analyzing train operation makes use of the so-called velocity profile concept. The energy associated with the momentum of a train moving on level, tangent track at a speed of V mph can be used in propelling the train to a certain height on an ascending grade. In texts dealing with mechanics this height “h” is termed velocity head, and the usual equation relating it to the velocity is given below.

$$h = 0.035V^2$$

where:

h = the head in feet

V = the train velocity, mph

- b. Suppose a train is about to accelerate from rest up to its balancing speed on level, tangent track. Its initial velocity head is zero, since it is at rest. By the time it has accelerated to a speed of 10 mph it has acquired a velocity head of 3.5 feet. If its balancing speed under the assumed operating conditions is 40 mph, when it reaches that speed its velocity head will have become 56 feet. If it soon encounters an upgrade it will decelerate to a lower speed and its velocity head will become less, unless the locomotive can deliver enough additional drawbar pull to overcome the grade resistance, in which case its velocity head will continue to be 56 feet. If the train is now braked to a stop the velocity head will become zero and the velocity profile terminates on the actual profile. This assumed performance is illustrated in [Figure 16-2-2](#).
- c. The assumed actual profile is represented by the line s-a-c-f. The curve s-b shows the velocity profile for the period of acceleration and operation at balancing speed. The curve b-d-f shows the effect of encountering the up grade and the final braking period. The dashed line b-e-f shows how the velocity profile would be affected if the locomotive could boost its tractive effort sufficiently to counteract the grade resistance up to the point of brake application.
- d. The relation between the velocity profile and the actual profile for any set of operating conditions is covered by the following rules:
- (1) While a train is accelerating, the profiles diverge.



(2) When a train maintains a constant speed, the profiles remain parallel and separated by a distance (head) equal to the velocity head computed for the constant speed.

(3) When a train decelerates, the profiles converge.

- e. The computation of points on a velocity profile curve is a time-consuming process even when special templates are devised and used. If the use of a computer is anticipated the necessary additional instructions should be added to the program previously mentioned in connection with the determination of the speed-time distance curves.

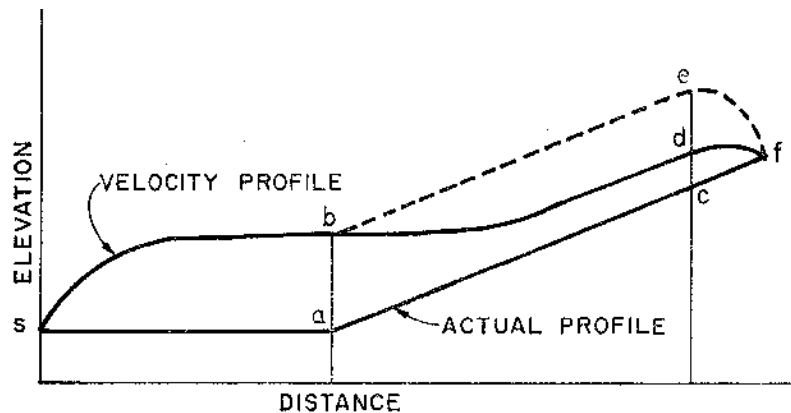


Figure 16-2-2. Velocity Profiles

2.2.3 TRAIN PERFORMANCE CALCULATIONS USING A COMPUTER (2004)

2.2.3.1 Introduction

Computers are ideally suited to rapidly and repeatedly evaluate the equations of motion that predict the performance of trains. Software that executes this task is generally known as a Train Performance Calculator (TPC). Such a computer program may be a stand-alone product, or may simply be a procedure used in a larger program. This is a must-have tool for anyone seeking to understand how a train operates over a specified territory.

2.2.3.2 Uses of a Train Performance Calculator

The ability to predict the performance of a train under a broad range of conditions makes TPC applications one of the most widely used simulation tools for a railroad. TPC software can be used for one or more of the following functions:

- Running time predictions as a function of locomotive and train consist, topography and speed limit. This information is widely used to perform many key railroad planning and analysis functions, including
 - Creating and evaluating passenger and freight train schedules
 - Predicting impact of changes to train or track speed limits
 - Evaluation of different horsepower-to-trailing ton policies
 - Unopposed run time inputs for train dispatching simulations (Note: Unopposed run time is the minimum time required for a train to complete its trip, adhering to all speed limits and performing all intermediate work, but ignoring interference with other trains.)

- Fuel consumption estimates
- Locomotive tonnage rating calculations
- Computation of stopping distance for use in determining proper spacing between block signals
- Evaluation of differences in train performance related to different types of equipment, including the effect of
 - Adhesion control systems
 - AC versus DC traction systems
 - Braking equipment (e.g., dynamic brake, electronically-assisted pneumatic brake, blended dynamic and air, and conventional air brake)
 - Diesel-electric versus electric propulsion
- Evaluation of proposed line changes, including vertical and horizontal alignment and superelevation

A limited number of TPC programs can perform very specific analysis, such as:

- Impact of technologies that reduce rolling resistance (e.g., flange lubrication, improved bearings)
- Impact of changes in track stiffness
- Impact of changes in train aerodynamics

TPC applications do not handle the following functions:

- Calculation of in-train forces (except rough estimates)
- Evaluation of train handling practices
- Evaluation of train make-up policies
- Effect of train consist and performance on track maintenance costs
- Modeling of train dispatching operations (e.g., resolving train meets and passes on single track)

However, these functions are available in other software packages that specifically address how cars within a train interact.

There are probably several hundred TPC programs in existence, since nearly all railroads and most railroad consulting firms own one or more versions. Versions are available for nearly all computer platforms, including mainframe, server, mini-computer and PC. Many are commercially available at modest prices from vendors, consultants and railroad trade organizations.

2.2.3.3 Overview of the TPC Program

The TPC program determines the performance of individual trains on a given track segment. Inputs to the software are:

- a. Track Data – specified by milepost or footage:





- (1) Track elevations and/or gradients
 - (2) Track curvature
 - (3) Permissible maximum track speeds
 - (4) Slow orders
- b. Train Data, including
- (1) Locomotive consists – specified by:
 - (a) Locomotive model names and the quantity and characteristics of each, or less desirably
 - (b) Aggregate locomotive characteristics, such as total horsepower
 - (2) Train consists – specified by:
 - (a) Car type and the quantity and characteristics of each, or less desirably
 - (b) Aggregate train characteristics, such as length and weight
 - (3) Scheduling and routing specifications, including the beginning and ending stations and intermediate stopping or consist-changing locations
- c. A program control environment affecting such things as:
- (1) Control parameters for the equations of motion, including the desired resistance formula
 - (2) Frequency with which equations of motion should be recalculated within the simulation (i.e., calculation step size)
 - (3) Frequency with which simulated results are output to the analyst

Using the above inputs, the TPC software calculates the equations of motion at regular, small time or distance intervals and outputs the results – location, elapsed time, speed and fuel consumed – to a data file or a user interface at the specified frequency. The running times calculated by the software generally represent the performance under average weather and track conditions (e.g., no snow, high wind or extremely slippery conditions).

2.2.3.4 Computational Methods Used in the TPC Software

Earlier sections of this chapter provided detailed descriptions of the forces acting on a train as it traverses a railroad line. The forces vary continuously as the train moves, making precise prediction of train speed difficult. However, if the net force on the train is calculated at a point on the track, the instantaneous change in the train's speed can be determined. With this information, the train's location at a later time can be estimated, and the net force on the train again calculated at that point. If the time (or distance) interval between these calculations is sufficiently small, train speed and location can be predicted. This is the approach used by all TPC applications to predict train speed and location:

- a. Calculate all propulsive and resistive forces at a point in the train's route,
- b. Determine the net force acting on the train,
- c. Determine the train acceleration using Newton's Second Law, $\text{Force} = \text{Mass} \times \text{Acceleration}$,

- d. Use the current train speed and acceleration to determine the train's position at a future time, and
- e. Iterate steps 1 through 4 until the train arrives at the termination point for the simulation.

In addition to its prediction of train speed and location, TPC programs manipulate throttle and brake settings to maintain the highest possible train speed, subject to speed restrictions and impending stops. To a large degree, the software replicates the actions which a locomotive engineer would take when operating the specified train over the specified territory. Among the behaviors the TPC software must reflect are:

- Operation of the train in the best possible manner. The locomotive is controlled so that it always hauls the train at the highest speed permitted by the given combination of tractive force and resistance but strictly obeying all the speed restrictions and slow orders, and accelerating the train no sooner than when the rear end clears the restricted area.
- Anticipation of the need for a brake application to maintain the current speed, enter a speed restriction or stop the train. The train brakes are controlled in the best possible way – bringing the train to the desired speed (or deceleration rate in the case of maintaining speed on a downward grade) exactly at the specified speed change point. In doing this, the TPC software must consider all grade and resistance forces the train will encounter between its current location and the point where the speed change must be accomplished.

2.2.3.5 Optional Features of TPC Programs

Because of the great utility of TPC software, many have been written by railroads, locomotive manufacturers, consultants and vendors since the first TPC software was developed in the late 1950's. While all utilize the same fundamental processing logic, versions differ in their treatment of various operational and modeling issues, among which are:

- a. Computational precision – A trade-off must be made between greater precision and faster computational speed. Shortcuts include:
 - (1) Representation of a train as a point-mass – Simplifies the computation of grade forces by placing all of the train's mass at a single point – the center of gravity of the train.
 - (2) Simplified representation of braking action and resulting forces
 - (a) Use of a single decelerative value (e.g., miles per hour per second)
 - (b) Instantaneous application and release of automatic brakes, eliminating calculation of propagation and build-up delays
- b. Inclusion of dynamic brake force in braking calculations – While having little effect on running times (i.e., a train's speed is little affected by which type of brake is used to generate the braking force), the use of dynamic brake will impact fuel consumption.
- c. Ability to consider head-end only speed restrictions – This can have a significant effect on running times if speed-restricted public grade crossings, separated by more than a train length, must be traversed. The ability of a train to accelerate from a restriction after only the engine has passed may produce significantly shorter run times than if the train accelerates only after the passage of the entire train.
- d. Replication of locomotive engineer behavior – Proper train handling procedures require a locomotive engineer to make smooth progressions through throttle notches, braking levels and the transitions between power and braking activities. Reproducing this subtle behavior is complex and computationally intensive. TPC programs often use shortcuts including:





- (1) Assuming power and braking force match demand at any instant – When a TPC program calculates the propulsive or stopping forces needed to bring the train to a target speed in each of its computational iterations, it may assume that the throttle and brake are instantly set to provide the needed force. Consequently, in rolling territories where conditions change continuously, the TPC software may change the throttle and brake positions rapidly, even moving instantaneously between power and brake actions. Clearly, this does not reflect the necessity to consider train-handling concerns.
 - (2) Ignoring the relationship between propulsive and stopping forces and specific throttle and brake positions, respectively – While a locomotive engineer typically works with discrete values (e.g., throttle notches and air brake positions), TPC programs may consider these values continuous. For such software, it would not be unusual for it to calculate the need for a propulsive force equivalent to a throttle notch of 7.5. Such averaging may affect the accuracy of both run times and fuel consumption.
- e. Range of output capabilities – All TPC programs output tabular results of speed, location and fuel consumed at the end of the simulated trip and at specified intermediate points. Some TPC software offers additional output options:
- (1) Graphical depiction of results, including
 - (a) Location versus Speed charts
 - (b) Location versus Speed Limit and Speed charts
 - (c) Location versus Speed and Throttle Position charts
 - (d) Location versus Elevation/Grade and Throttle/Braking Position charts
 - (2) Animation during simulation – Some TPC programs permit the analyst to view the train as it runs, enabling a visual check that the train's operation is being simulated correctly.
 - (3) In-Train Force Estimates – TPC software may provide approximations of the highest longitudinal force within the train to indicate existence of a dangerous condition (e.g., break-in-two, high buff force).
 - (4) Interactive and batch processing options – Some TPC software will simulate only one train (i.e., a single input and output data stream), while others will simulate the movement of hundreds or thousands of individual trains sequentially in a “batch” process.
 - (5) Choice of a variety of propulsion systems, including electric locomotives and electric traction – Note that the performance of electrically-propelled trains will be impacted by the quantity of trains using the power distribution network, and that the TPC software may need to interact with a power distribution simulation.
 - (6) Ability to develop runtime formulas and charts – For a given set of speed limits, the run time over a specified track segment is strictly a function of a train's horsepower-to-trailing-ton ratio (HP/TT). If trains are simulated with HP/TT values ranging from a low just above train stall, a high representing the highest HP/TT value used on the railroad and several values in between, a smooth curve can be plotted. Regression analysis can fit an equation to this curve, permitting run time estimates to be easily calculated. The equations are sufficiently accurate to serve as inputs to train scheduling and dispatching software.

2.2.3.6 Calibration of TPC Programs

It is good practice to use TPC software that has been calibrated, i.e., one that has demonstrated an ability to accurately predict running times and fuel consumption. Some have been rigorously tested, while others may be largely uncalibrated. If the analyst is uncertain whether the TPC software has been adequately calibrated, it is recommended that the analyst perform a simple calibration procedure before adopting the model:

- a. Gather data on a variety of actual trains on disparate territories,
- b. Define the key characteristics of each train and input these to the TPC software,
- c. Compare actual train run times with simulation results, and
- d. Determine whether run time differences fall within an acceptable range or can be explained by extraneous events (e.g., train delays, bad weather, etc.).

The accuracy of fuel consumption calculations is more difficult to ascertain. Recording the difference in fuel gauge measurements at the beginning and end of a trip may be useful, but fuel gauges often prove to be unreliable. If a train event recording is available at the end of a trip, it will be extremely useful for calibration using the following procedure:

- a. Determine the amount of time that each locomotive in the consist spends in each throttle notch, including idle, during the trip; also record how long the dynamic brake is in use.
- b. Determine the fuel burn rate (i.e., gallons or liters per hour) for each locomotive in each throttle notch, using fuel consumption tables from the locomotive manufacturer.
- c. Multiply the time in each throttle notch by the corresponding fuel burn rate, and compare this figure with simulation results.
- d. Determine whether fuel consumption differences fall within an acceptable range or can be explained by extraneous events (e.g., train delays, bad weather, etc.).

2.2.3.7 Need for Precision in TPC Programs

With few exceptions, railroads do not operate as precision machines. Key inputs to TPC software – car weights, locomotive and vehicle characteristics and topographic features – are seldom precisely known and may change over time. Given the uncertainty of the inputs, TPC software that provides a reasonable level of precision will prove to be suitable for most purposes.

In practice, it has been found that relatively unsophisticated TPC software produces results within ten percent of those generated by more precise algorithms, and that this level of accuracy is quite acceptable for most studies. When more precision is required – e.g. investigating train accidents – a different but related type of simulation – a train action model – should be used.

Many railroads are now using digital computers to calculate the running times of trains as a basis for determining and evaluating schedules. The methods have become identified by the term TPC (train performance calculator).

2.2.4 FIELD TESTING WITH DYNAMOMETER OR TEST CARS (2008)

- a. A dynamometer car is a railway car of special design that is usually placed at the head end of a train immediately behind the locomotives. The drawbar pull of the locomotive consist, which is transmitted to the train through the dynamometer car, can be measured accurately and its value recorded on a moving chart or other recording equipment as a function of time or distance traveled. Instrumentation may also be provided to record train speed, the total work performed, air brake pressure, train location, locomotive performance, and other operating variables of special interest. Information obtained by this means can be useful for determining train resistance at various speeds, as well as locomotive efficiency and hauling capacity under varying weather, topographic, and loading conditions.
- b. Older dynamometer cars that collected and recorded data mechanically are mostly out of service. The newer cars that remain collect and display data electronically, or by a combination of electronic and mechanical means, depending on the design of the car.





- c. Dynamometer cars were once used extensively with steam locomotives, primarily to evaluate the myriad designs and develop tonnage ratings, but this need has mostly disappeared with diesel locomotives. Because diesel locomotive performance deviates only minimally from the manufacturers' specifications, and is less affected by maintenance, and because a diesel has a greater reserve of power at low speeds, the tonnage ratings for diesel locomotives can usually be calculated within an acceptable range of accuracy without requiring check measurements. In addition, newer technologies such as on-board locomotive computers to record diesel operating functions, the use of train performance calculators, and the ability to download data via laptops, radio links, or satellite have reduced the need for field measurements.
- d. Modern dynamometer cars, more commonly called test cars, are still used by railroads and equipment vendors to evaluate new locomotive designs, and as a periodic check to verify locomotive performance under actual operating conditions. Stopping distances and new types of equipment such as electronically controlled pneumatic brakes, train handling guidance systems, and communication-based train control can also be evaluated. Newer types of testing can include exhaust emission monitoring, and locomotive fuel consumption. Test cars may also incorporate some of the instrumentation of track geometry cars to evaluate interactions between track and vehicles.
- e. If used to measure locomotive performance, test cars are typically placed behind the locomotive consist, or even within the consist to be closer to a particular locomotive of interest. However, if used as an instrument platform to measure items such as in-train forces, car rocking, vibration, or ride quality, test cars may be placed elsewhere in the train. Caution is required when using passenger type cars mid-train because of the risk of derailment or injury to car occupants due to high in-train forces or severe slack action.
- f. If used as an instrument platform, it is recommended that test cars be permanently equipped with the basic equipment, including instrumented dynamometer couplers, to monitor train speed, brake activity and locomotive activity either through a standard 27 pin jumper or via a radio link. Data acquisition equipment, power supplies, and the appropriate displays should also be included. Connections and deck space should also be provided for temporary equipment for more specialized tests. It is also a good idea to equip the car with through connections for the standard MU cable and through MU pipes for the brake system such that the car can be placed within a locomotive consist.
- g. For dynamometer readings within a train, it may also be possible to install calibrated couplers with data collection capabilities on any rail car to avoid the need for a test car.

SECTION 2.3 FUEL CONSUMPTION

2.3.1 ELECTRIC LOCOMOTIVES (1970)

2.3.1.1 Energy and Power Requirements on Straight, Level Track; with Constant Speed Operation

Under revision.

2.3.1.2 Constant Speed Operation on a Long, Uniform Grade

Under revision.

2.3.1.3 Effect of Curves

Under revision.

2.3.1.4 Force Required to Accelerate a Train on Straight, Level Track

Under revision.

2.3.1.5 Energy Required to Accelerate a Train from Standstill to Its Balancing Speed (Reference 19, 27, 75, and 79)

- This is a long and tedious process if determined from step-by-step calculations. It is likely, however, that much of this work can be eliminated by making certain simplifying assumptions and then programming the data for a computer.
- To illustrate the step-by-step method, let it be assumed that the locomotive manufacturer has provided a curve of locomotive tractive effort in pounds at the rim of drivers vs. speed in miles per hour, such as is shown in Figure 16-2-3.

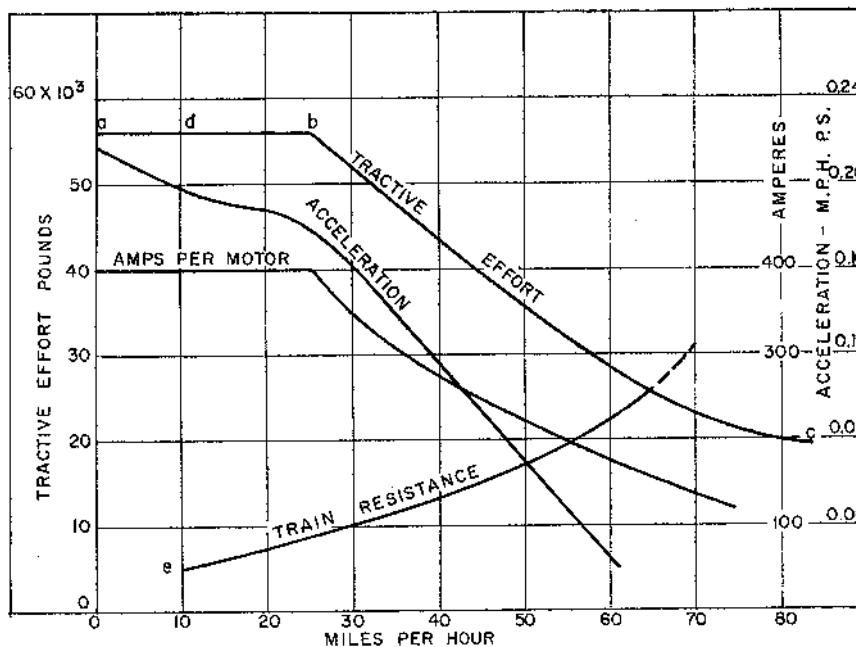


Figure 16-2-3. Locomotive Tractive Effort in Pounds vs. Speed in Miles Per Hour

- The portion a-b of the curve shows the expected behavior while the controller is in use and it is assumed that the notching-out process is carefully and skillfully handled, so that the current drawn by each motor is held practically constant. The shape of the curve from b to c is governed by the speed-torque relationship of the motors themselves.
- For simplicity let it also be assumed that the locomotive train resistance curve has the same equation as the curve for the trailing load; and that the train is accelerating on straight, level track. It then becomes possible to add the locomotive weight to the trailing tonnage and plot total pounds of resistive effort vs. speed. The intersection of these two curves marks the balancing speed, and the vertical distance between the two curves (for example the distance d-e at 10 mph) gives the tractive effort available for acceleration at that speed, giving the magnitude of F in the equation:

$$F = 100 WA$$

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where:

F = accelerating force, in pounds

W = train weight, in tons

A = acceleration in miles per hour per second

- e. Since W is known for the specific trailing load and locomotive being considered, a curve of acceleration vs. speed can easily be plotted. For example, assume the train weight for the illustrative case is 2,570 tons. Then the acceleration when $V = 10$ mph is 0.198 mph. Other points can be computed in the same manner, and the acceleration curve of [Figure 16-2-3](#) is obtained.
- f. To obtain points on the speed-time curve, so that the time required to reach balancing speed can be determined, the step-by-step procedure may be employed:
 - (1) Choose a convenient velocity increment, say 10 mph.
 - (2) From the acceleration curve on [Figure 16-2-3](#) read the average acceleration during this velocity interval. For the chosen example this average will be about 0.208.
 - (3) Divide the selected velocity increment by this average acceleration, obtaining 48 sec, which is the time, starting from standstill, to reach 10 mph.
 - (4) Perhaps the next velocity increment should be smaller for greater accuracy, say 5 mph. From the curve the average acceleration is about 0.194 and the time to increase the train speed from 10 to 15 mph will be 26 sec. The total elapsed time is now 74 sec.
 - (5) Additional velocity increments should be chosen and this process repeated. The data thus obtained may be plotted. For the chosen example this curve is shown in [Figure 16-2-4](#), and it will be noted that the time to reach the balancing speed of 65 mph is about 885 sec.
- g. The next step in determining energy utilizes the motor current-speed characteristic, which will be furnished by the locomotive manufacturer. A typical one has been plotted in [Figure 16-2-3](#), which indicates that the current per motor may be expected to remain practically constant while the controller is being notched out (up to 25 mph in this case), and then falls off with increasing speed. Using the speed-time curve of [Figure 16-2-4](#), a curve of current vs. time may be obtained, such as is shown on [Figure 16-2-4](#).
- h. To obtain watt-hours of energy drawn from the trolley while accelerating up to balancing speed, the information obtained for one motor in [Figure 16-2-4](#) must be transformed to trolley current for all motors on the locomotive by considering their connection pattern while the controller is in the circuit and also for the subsequent period up to balancing speed.
- i. The final step is multiplication of the trolley ampere-seconds (measured by the area under the curve of trolley current vs. time) by trolley voltage, and then dividing by the average motor efficiency.
- j. This method can be extended to take grades and curves into account.

2.3.2 DIESEL LOCOMOTIVES (2009)

Diesel fuel and labor are the two largest operating costs to the railway industry. The increasing cost of fuel, combined with the increasingly restrictive environmental regulations affecting locomotive emissions, render it imperative to control fuel consumption by improving fuel efficiency and eliminating waste. Part of this process requires an understanding of fuel consumption over existing or proposed routes, and the variables that affect fuel consumption.

Four approaches for estimating fuel consumption over an existing or proposed line are:

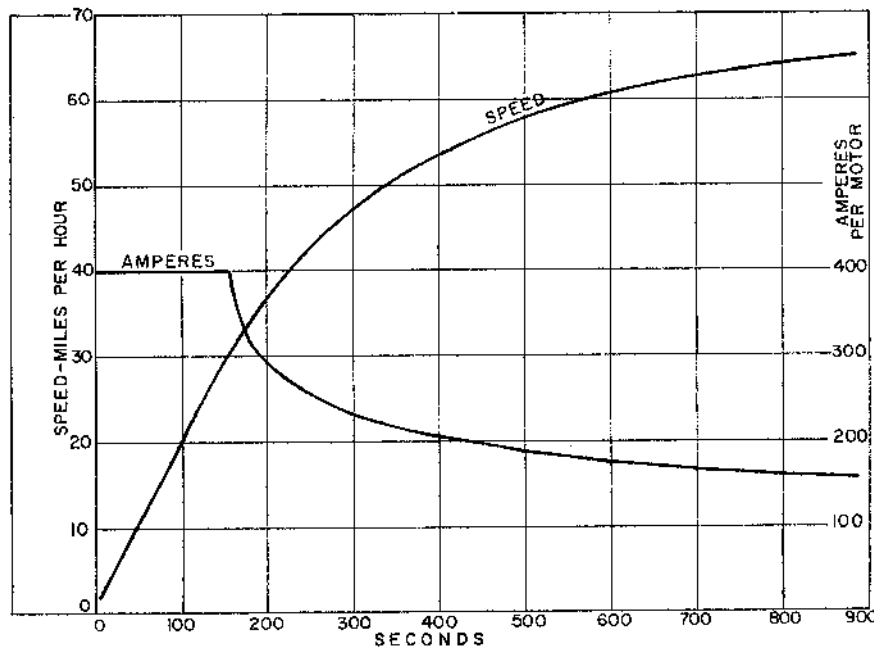


Figure 16-2-4. Speed-Time Curve

- The Poole Energy Formula (PEF) - estimate foot-pounds of work required to move a train over a specific line and apply an empirically determined fuel consumption factor per million foot-pounds.
- The Fuel Consumption by Throttle Position (FCTP) approach - estimate the time in each throttle position throughout the run and apply empirically determined gallons consumed per hour in each throttle position.
- Train Performance Calculator (TPC) - simulations over existing or proposed lines, with fuel consumption outputs based on locomotive performance.
- Measurements – monitor of actual fuel consumed over an existing line using test cars or other measuring methods.

2.3.2.1 Poole Energy Formula (PEF) ([Reference 65](#))

To estimate fuel consumption using the foot-pounds of energy required to traverse a given line of railroad, follow the procedure outlined below for each direction separately:

- Tabulate the gradients (in feet of rise (+) or fall (-)) and degrees of curvature, mile post to mile post.
- Start with the sum of the ascending (+) grades (feet).
- Add the product of 15.84¹ feet per mile times miles of road.

¹ The 15.84 feet of resistance in Section 2.3.2.1e and Section 2.3.2.1f is the resistance for a straight and level mile which was derived from extensive dynamometer tests and is recommended by AREMA.



- d. Add the product of the total degrees of central angle (excluding degrees of curvature on descending grades in excess of 16 feet fall per mile) times 0.04 foot per degree of central angle.
- e. Subtract 60% of sum of the feet of fall on descending grades between 0 and 16 feet per mile.
- f. Subtract the product of 11.088 feet (70% of 15.84)¹ times the number of miles of descending grades of 16 feet per mile or more.
- g. Multiply results of paragraph b, paragraph c, paragraph d, paragraph e, and paragraph f by total train weight in millions of pounds.
- h. For average operating speeds of approximately 35 mph, multiply total energy in foot-pounds by 0.034 gal. per million foot-pounds.

2.3.2.2 Fuel Consumption by Throttle Position (FCTP)

- a. At each throttle position a diesel engine injects a metered amount of fuel into the cylinders. The fuel consumption per hour in each throttle position may be obtained from locomotive manufacturers based on test stand data. If one can make a reasonable estimate of the total time in each throttle position, the fuel consumption for a run can be calculated.
- b. The estimate of time in each throttle position may be obtained from the following:
 - By examining the proposed profile in consultation with an experienced road foreman of engines
 - From the indicated throttle position on a TPC printout. (See [Section 2.2.3.](#))

2.3.2.3 TPC Simulations

- a. Both the PEF and FCTP methods of estimating fuel consumption are labor intensive to use and limited in their accuracy. They provide approximations of fuel consumption but neither method considers all of the variables affecting fuel consumption in actual operations. Furthermore, original Poole conversion rate from foot-pounds to gallons may no longer be accurate with the more fuel-efficient locomotives of today. The PEF and FCTP may have some historical interest but they have been mostly supplemented by more accurate and more efficient methods of estimating fuel consumption.
- b. TPC simulations designed to estimate fuel consumption take into account the route data required by the PEF as well as locomotive types, tonnage, and speeds to calculate fuel consumption over a given territory. The proper simulation model eliminates the need to manually calculate FCTP on a TPC print-out because fuel consumption is already calculated as an output from the simulation.
- c. TPC simulations are an effective way of estimating fuel consumption and the effect of operating or design changes, especially on routes that do not exist. However, even sophisticated simulations may not take into account all of the variables affecting fuel consumption in actual operations.

2.3.2.4 Actual Measurements

- a. For existing routes, measurements with actual trains are the most accurate way to measure fuel consumption, especially when evaluating new locomotives. The simple way of measuring fuel consumption by comparing fuel in the tank at the start of a run with fuel remaining at the end is one way to measure fuel consumption but it depends on the accuracy of fuel tank gauges and may not explain the impact of all variables.

¹ The 15.84 feet of resistance in Section 2.3.2.1e and Section 2.3.2.1f is the resistance for a straight and level mile which was derived from extensive dynamometer tests and is recommended by AREMA.

- b. Measuring fuel consumption by instrumentation or test car is perhaps the most effective to measure actual fuel consumption. Properly instrumented test cars can indicate fuel efficiency based on locomotive performance but also can account for operating variables such as train resistance due to tonnage and train make-up dynamics, train handling, delays in sidings, weather conditions, and shutdown policies. An understanding of actual fuel consumption for different trains over a given territory can be particularly useful in locating and designing fueling facilities. (See [Section 2.2.4.](#))
- c. Minimum fuel consumption may not always be the best choice when all commercial and operating requirements are considered. For example, higher horsepower to ton ratios may be desirable to provide the necessary service for time sensitive freight, and higher running speeds may be appropriate for efficient dispatching or to avoid the need to re-crew a train, even if fuel efficiency must be sacrificed. TPC runs and theoretical fuel calculations are a good starting point, but may not reflect fuel efficiencies of actual operations.

2.3.2.5 Fuel Costs and Conservation

- a. Regardless of the economics of fuel efficiencies, it is always prudent to control fuel costs and minimize environmental effects with well-managed fuel conservation programs to eliminate losses and waste. These programs might include methods to measure and control fuel inventories, optimize purchasing and fueling strategies, eliminate potential spillage at fueling locations, implement effective locomotive shutdown policies, build trains to reduce resistance, shut box car doors, train engineers on handling procedures to conserve fuel, and recognize and reward leaders in fuel conservation.
- b. Intermodal trains offer unique opportunities for fuel conservation because they are typically the fastest freight trains operated by North American railroads, but tend to have the poorest aerodynamic characteristics. Because of constraints imposed by equipment design and diversity, intermodal trains incur greater aerodynamic penalties and increased fuel consumption when compared to other trains. It has been found that improving the loading patterns of intermodal trains has the potential to improve aerodynamic characteristics and thus fuel efficiency. Depending on the particular train configuration, studies suggest that train resistance might be lowered by as much as 27% with fuel savings up to 1 gal/mile per train.
- c. The following are general guidelines for loading intermodal trains to increase their aerodynamic performance:
 - Place loads with shorter gaps in the frontal position of the train to generate less aerodynamic resistance (especially for the first 10 gaps).
 - For well cars, place longer loads on top of shorter loads if possible because the upper level gap has more significant impact on aerodynamic drag than lower level gap.
 - Match intermodal loads with cars of an appropriate length to maximize slot efficiency, where slot efficiency is defined as the ratio of the actual load length to the ideal load length for each slot.

Commercial requirements may preclude a perfectly optimized train from an aerodynamic perspective, but recognizing the opportunities for potential savings can still lead to better fuel efficiency.





American Railway Engineering and
Maintenance-of-Way Association



Part 3

Power¹

— 1983 —

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¹ References, Vol. 71, 1970, p. 425; Vol 84, 1983, p. 104. Adopted 1970.

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SECTION 3.1 GENERAL

3.1.1 TYPES OF MOTIVE POWER (1970)

- a. The principal types of motive power used by American railroads are electric, diesel-electric, gas turbine-electric, and diesel-hydraulic locomotives; and diesel-hydraulic, and electric rail cars.
- b. In order to compare the operating characteristics of different types of locomotives, or to study the economic problems associated with their use on various line locations and gradients, it is necessary to become familiar with a few basic terms and concepts. It may also be necessary to understand the methods of calculating speed-tractive effort curves for these locomotives if such data are not readily available from the manufacturer.

3.1.2 HORSEPOWER (1970)

- a. Locomotives are generally rated in terms of their horsepower.
- b. In electric locomotives the rated horsepower is the power available at the rims of the drivers.
- c. In diesel- or turbine-electric locomotives the rated horsepower is that which is input to the main generator for propulsion.
- d. The power exerted by a locomotive at the rims of the drivers is called rail horsepower.

3.1.3 TRACTIVE EFFORT (1970)



- a. Tractive effort is the propelling force which a locomotive exerts at the rims of its driving wheels. It is usually expressed in pounds.
- b. The relation between tractive effort, rail horsepower, and speed in miles per hour is:

$$\text{Tractive effort} = \frac{(375)(\text{Rail horsepower})}{\text{Speed}}$$



- c. Drawbar tractive effort is the pulling force exerted at the rear drawbar of the locomotive, that is, the rail tractive effort less the effort necessary to move the locomotive itself.

3.1.4 ADHESION (1970)



- a. The adhesion of a locomotive is the ratio of the tractive effort needed to slip the drivers to the weight on the drivers. It is usually expressed in percent. Under poor rail conditions (when the rail is both oily and wet) it may amount to less than 5%, whereas under exceptionally good conditions it may exceed 40%. Poor rail conditions can be improved by the use of sand or by chemical treatment, so that it may be assumed that maximum tractive efforts of 25 to 30% of the weight on drivers can normally be exerted without slip and will thus be available for starting trains.



- b. With the train in motion, wheel slip may occur at tractive efforts well below the starting maximum, due to imperfections in track alignment and wheel bouncing. That is, adhesion becomes smaller as speed increases. At 60 mph, for instance, adhesion may be 15% or lower, even with good rail conditions.

3.1.5 LOCOMOTIVE CAPACITY (1983)



- a. The rail horsepower which a locomotive can develop depends upon the nature and location of the prime source of power and upon the type and design of the locomotive. Electric locomotives receive their power from an outside source which is ordinarily assumed to have unlimited capacity. In the case of diesel-electric locomotives, however, all the power comes from a source on the locomotive itself. Thus, rail horsepower is limited by the available shaft horsepower of the diesel engine.
- b. All locomotives must convert this prime power into mechanical power for application to the driving axles. The theoretical capacity of any locomotive which is not already rated in terms of rail horsepower must, therefore, be modified by the characteristics of the power-converting equipment and the losses associated therewith. For diesel-electric locomotives this transmission efficiency is in the range of 80 to 85% and will vary with the track speed of the locomotive.
- c. The rail horsepower available for starting and moving a train is also limited by the adhesion between the driving wheels and the rail. In diesel-electric and electric locomotives rail horsepower is further affected by the operating temperature and commutation limitations of the traction motors.
- d. Where two or more locomotive units are used on the same train, it is customary to rate the combination as the sum of the individual ratings. An exception to this rule must be made, however, when this would reduce train speed below the minimum continuous speed for any one of the units. In that case each locomotive must be rated at a speed corresponding to the highest minimum continuous speed of the various units involved.

- e. Three factors are important in determining the performance of locomotives in any type of service.
 - (1) Rail horsepower determines how much time a locomotive requires to haul a train of given tonnage between two points.
 - (2) Tractive effort determines how much tonnage a locomotive can handle and is of particular importance on ascending grades.
 - (3) Adhesion determines how much of the potential tractive effort can be used and is of particular importance in starting and at low speeds.

3.1.6 LOCOMOTIVE CLASSIFICATION (1983)

The Standard locomotive classification system is a more recent system devised to avoid confusion in distinguishing between driving and nondriving axles. In this system letters are used to indicate the number of driving axles and numbers to indicate the idle axles. Hyphens are used to indicate the separation of axles into groups. Thus 2-D-2 indicates a locomotive having a group (probably a truck) of two guiding axles, then a group of four driving axles, and finally a group (or truck) with two more guiding or idle axles. If one or more axles on a guiding or trailing truck are motor driven, letters are employed to indicate this. Thus 1A-C-A1 designates a locomotive in which the pilot and trailing trucks each have one idle axle and one motor-driven axle, and the main or center truck has three driving axles. Modern Diesel-Electric locomotives generally are either B-B or C-C.

SECTION 3.2 ELECTRIC LOCOMOTIVES

3.2.1 GENERAL (1983)

- a. Two general power distribution systems are used on the electrified railways of the North American continent; namely, the direct-current and the alternating-current systems. Current collection may be accomplished through the medium of collector shoes sliding on a third rail, or by use of a pantograph or trolley wheel in contact with an overhead trolley wire.
- b. There are four distinct types of electric locomotives of sufficient importance to warrant mention here:
 - (1) those equipped with d-c traction motors fed from a d-c system,
 - (2) those equipped with single-phase a-c traction motors fed from a single-phase a-c contact system,
 - (3) those equipped with d-c traction motors fed through rectifiers from a single-phase a-c contact system,
 - (4) those equipped with d-c traction motors fed from a d-c generator which is mechanically driven by a single-phase a-c motor receiving current from a single-phase contact system.
- c. Though single electric locomotive units can be built to very large size, it is also possible to operate two or more locomotive units in multiple under a single control.

3.2.2 OPERATING CHARACTERISTICS (1970)

3.2.2.1 Horsepower Ratings

- a. The horsepower ratings for electric locomotives are expressed in terms of rail horsepower at a specified speed. One-hour or short-time ratings are usually given also. These ratings are governed by the maximum safe temperature rise in the motor windings, which in turn is governed by the length of time they are required to carry current, the amount of current, and the means provided (usually forced ventilation) to



dissipate the heat thus produced. It follows that if the ambient temperature is low the safe horsepower loadings may be increased.

- b. Figure 16-3-1, Figure 16-3-2, and Figure 16-3-3 show typical curves of rail horsepower vs. speed for different types of electric locomotives.

3.2.2.2 Locomotive Capacity

- a. Since electric locomotives draw their power from an external source having an extremely large capacity, the locomotive capacity is normally limited only by the amount of power that can be used without slipping the drivers and by the commutation and temperature limitations of the traction motors. Since it takes an appreciable time to reach dangerous operating temperatures in any case, traction motors usually have large short-time overload capacities.
- b. Because of the non-pulsating torque created by electric traction motors and the possibility of good weight distribution on all drivers, the adhesion limit for electric locomotives is relatively high. In most instances a conservative figure of 25% is assumed for a locomotive starting a train on a wet rail with sand, and 30 to 35% on a clean dry rail. A lower figure of perhaps 20% is more appropriate for continuous hauling.

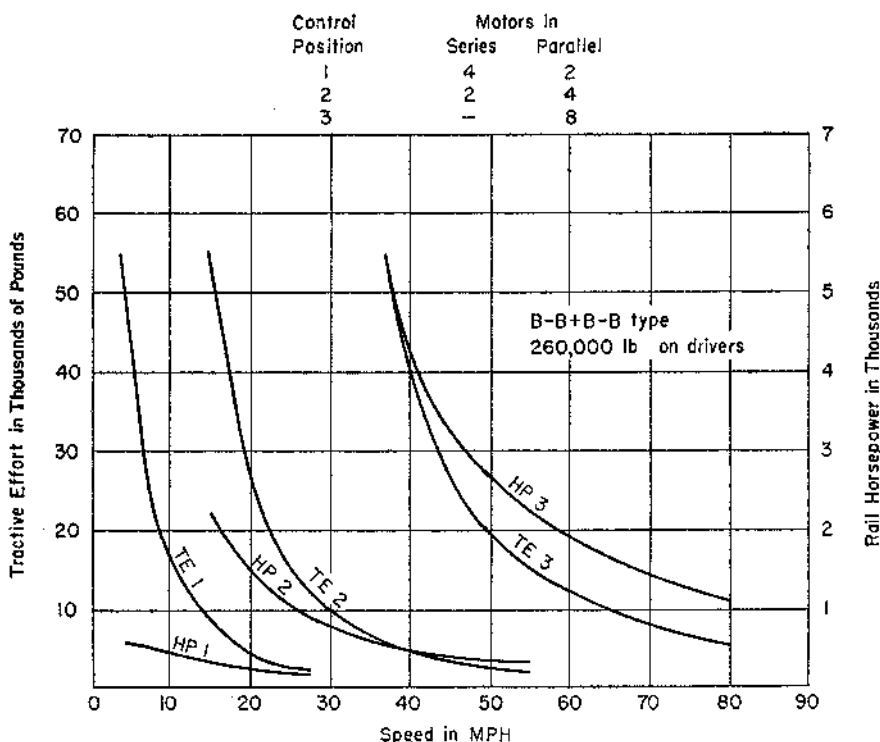


Figure 16-3-1. Tractive Effort and Horsepower Curves for a 600-v d-c Locomotive with Series-Parallel Control

3.2.2.3 Minimum Continuous Speed

- a. Among the factors affecting the speed at which an electric locomotive can pull a train, the most important is the tractive effort required to overcome the drag of the train. An increase in tractive effort can only be secured by an increase in traction motor current, and this is normally accompanied by a decrease in speed. If the tractive effort requirement increases to such an extent that the current needed to produce it reaches the continuous current rating of the traction motors, the speed at which the locomotive is then operating may be termed its minimum continuous speed.

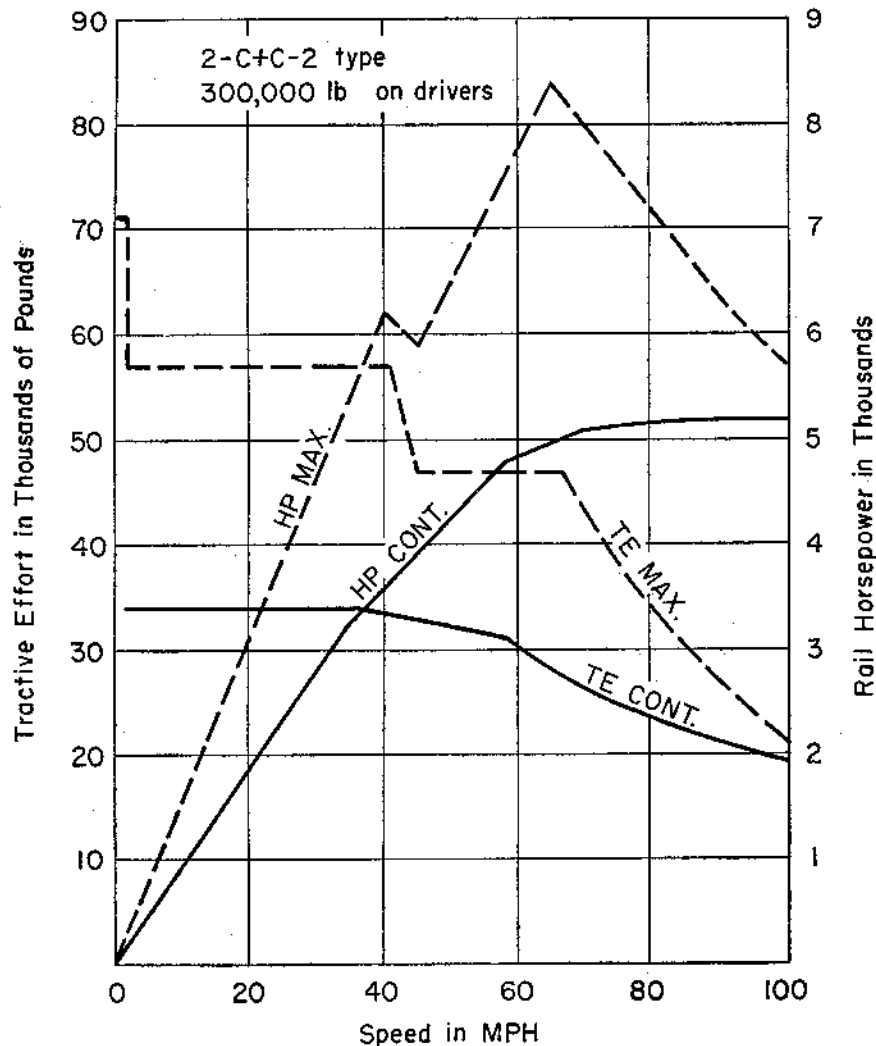


Figure 16-3-2. Tractive Effort and Horsepower Curves for a Single-phase a-c Locomotive (11,000 v, 25 Hertz)

- b. This definition of minimum continuous speed is reasonably satisfactory for d-c locomotives using a series-parallel type of controller without field weakening. Many electric locomotives have controllers which permit the selection of several motor voltages or several motor field strengths, however, and there will usually be a minimum continuous speed for each of these controller settings. Hence the term “minimum continuous speed” is somewhat ambiguous when applied to electric locomotives in general.

3.2.2.4 Gearing

- a. Some electric locomotives have been built with the motor armatures mounted directly on the driving axles. This design has not been followed in recent years. Modern locomotives have the motor armature shaft coupled to the driving axle by spur gearing, with a small gear or pinion on the armature shaft meshing with a large gear on the driving axle. This arrangement permits the use of a high-speed armature which gives greater horsepower per pound of motor weight. Usually each driving axle is geared to one motor, though at least one railroad employs locomotives having twin motors engaging each driving axle through spur gears.

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