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 2-1.

Table 2-1. Coefficient Contributors

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

2.1.2 DAVIS FORMULA – HISTORIC DEVELOPMENT (1992)

a. In 1926, W. J. Davis (Bibliography 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 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 (Bibliography 80) and Totten (Bibliography 79) 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 (Bibliography 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 (Bibliography 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.

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

where:

Rr = 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 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 2-2. Values of C Coefficient For Use with Canadian National Train Resistance Formula Only

(Bibliography 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 2-3. The table shows in more detail recommended Canadian National values for C and cross-sectional areas for the various equipment types.

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

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

(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:

$$R\ aero = CV^2 = 0.5\rho(CDa)V^2$$

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 (Bibliography 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)

a. 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.

b. 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)

a. 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 (Bibliography 13):

$$Rc = 0.17\ (gage)$$

where:

Rc = Curve resistance in lb/ton per degree of curvature
gage = gage in feet

b. 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 (Bibliography 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 (Bibliography 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 (Bibliography 29) and other references listed in Bibliography.

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 (Bibliography 60). Table 2-4 shows Canadian National C values for typical tunnel situations.

a. In Table 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 2-4 are lower than those given in Table 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 2-4. Typical Values of C Coefficient in Tunnels For Use with Canadian National Train Resistance Formula Only

(Bibliography 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 (Bibliography 62).

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 (Bibliography 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 (Bibliography 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 (Bibliography 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 (Bibliography 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 Cld and the C coefficient for trailing vehicles is Ctr, the overall C coefficient for such a combination will be:

$$\text{C combined} = \frac{\text{Cld} + (\text{n} - 1)\text{Ctr}}{\text{n}}$$

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.