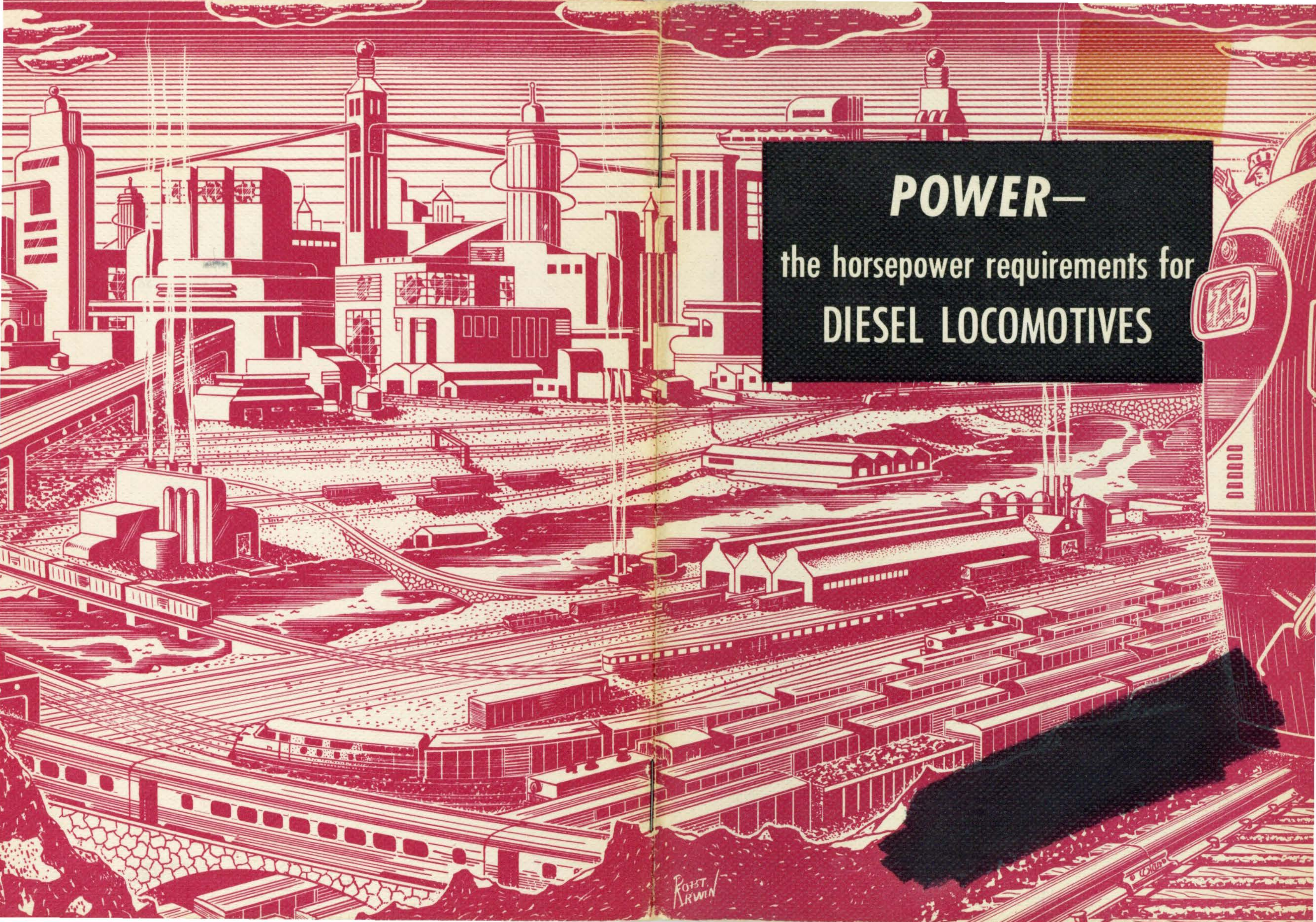
POWER–

the horsepower requirements for DIESEL LOCOMOTIVES

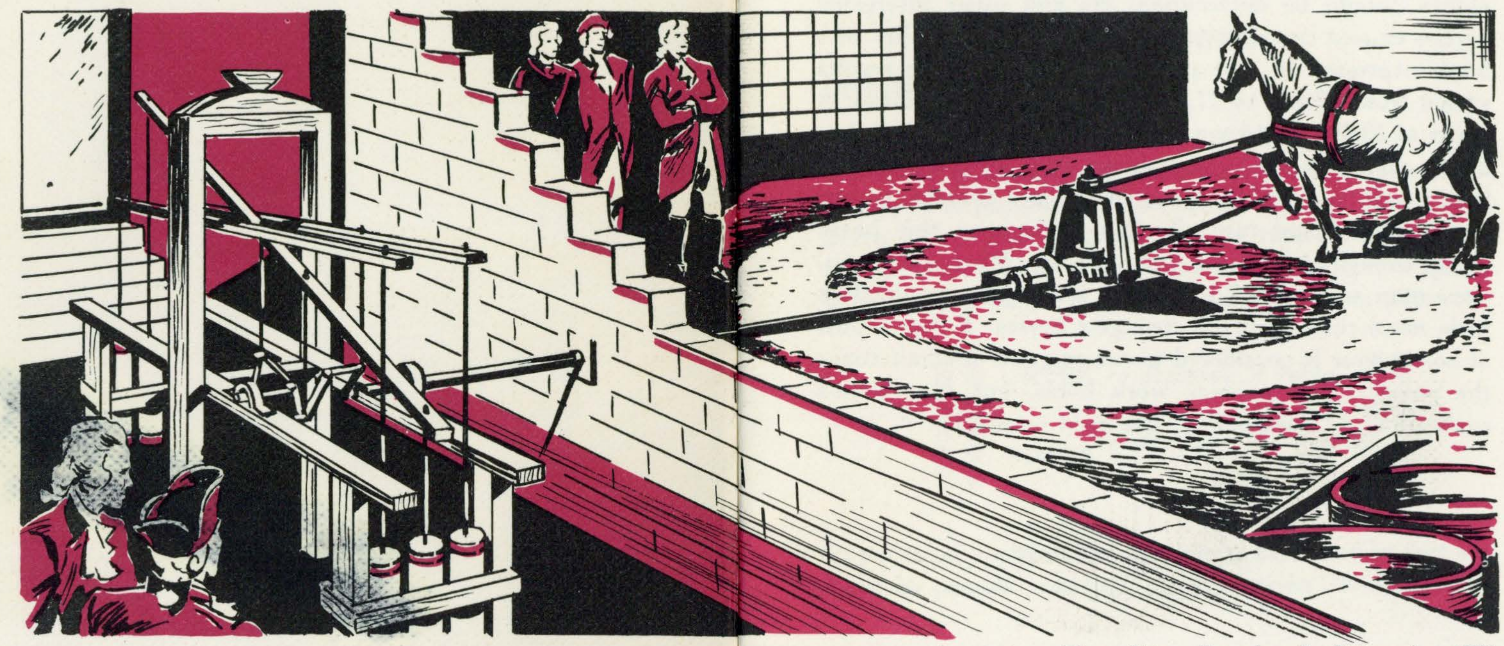


"The Diesel engine has doubled the resources of mankind as regards power production and has made new and hitherto unutilized products of nature available for motive power. I must call to your mind the fact that nowhere in the world are the possibilities for this prime mover as great as in the United States."

Rudolph Diesel—1912

THE TERM "horsepower" as applied to Railroad Motive power can have many meanings and interpretations. When comparing the performance of steam and Diesel locomotives, horsepower designations are frequently confusing. A factual discussion of horsepower ratings and what horsepower means in the overall job of moving trains will promote a better understanding of Diesel locomotive requirements.

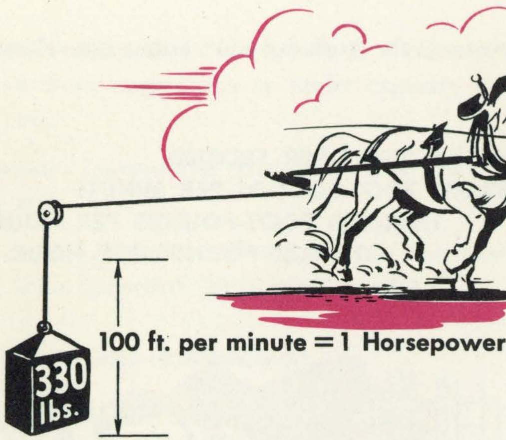
The term "horsepower" came into existence when steam engines began to replace horses for pumping water from English mines.



From description—First edition, Encyclopedia Britannica, 1771

Captain Thomas Savery is believed to be the first person to suggest the method of expressing the power of an engine with reference to that of horses. This was in 1702, about four years after Captain Savery received one of the earliest British steam engine patents. For the next seventy or eighty years, steam engines were rated after they were installed. When an engine was capable of performing a certain amount of work in the same time as a given number of horses, it was said to be an engine of so many horses' power.

Shortly after the firm of Bolton and Watt began the business of manufacturing steam engines in 1773, Mr. Watt realized that some definite method of rating an engine's ability should be determined. He and other interested parties caused certain tests to be made of the ability of a horse expressed in foot pounds per minute. The results varied from 17,400 to 27,500 foot pounds per minute. A figure of 22,500 foot pounds per minute was considered to be the ability of the average horse. Mr. Watt decided his firm would use 33,000 foot pounds per minute as one "horsepower" and rate all their engines on this basis. Many thought 33,000 too high, but Mr. Watt was a cautious man and wanted to be sure his engines would do a little more than even the strongest horses. Today a unit of horsepower is considered about one and one half times the power of an average work horse, but Mr. Watt's evaluation of "horsepower" has been retained.



DEFINITIONS

HORSEPOWER

Unlike most physical laws, the term horsepower is the expression of an arbitrary but accepted unit of power that is defined in physics books as being the work necessary to move 330 pounds vertically at the rate of 100 feet per minute. This indicates that Work becomes Power when the work is done within a certain time element as follows:

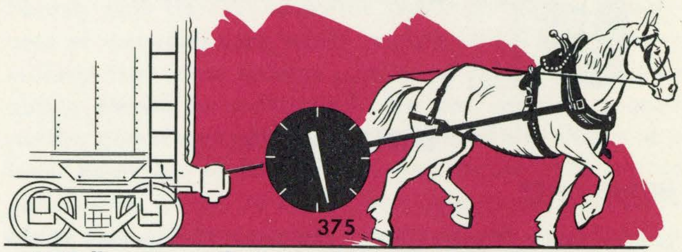
$$\textbf{WORK} = \textbf{distance} \times \textbf{force}$$

$$\textbf{POWER} = \frac{\textbf{distance} \times \textbf{force}}{\textbf{time}}$$

In practical applications, distance is expressed in feet and force in pounds, creating the expression "foot-pounds".

One horsepower is the work done in various time elements as follows:

550 FOOT-POUNDS PER SECOND
33,000 FOOT-POUNDS PER MINUTE
1,980,000 FOOT-POUNDS PER HOUR
375 MILE-POUNDS PER HOUR



375 lbs., one mile in one hour = 1 horsepower

$$\frac{375 \times 5{,}280}{33{,}000 \times 60} = 1$$

LOCOMOTIVE RATING

During the past several years there have been many suggestions that a uniform method of horsepower rating be adopted for the various types of locomotives now available, but to date no action has been taken. The following are the commonly accepted methods of rating:

Diesel Locomotive Horsepower is the power input to the main generator for propulsion only.

Steam Locomotive Horsepower is a computed figure derived from engine size or boiler capacity or an average of both.

Electric Locomotive Horsepower is that available at the rails.

Turbine Locomotive Horsepower is the power input to the main generator for propulsion only.

DIESEL ENGINE HORSEPOWER

The Diesel engine, often referred to as the Prime Mover, furnishes power for various necessary auxiliary equipment and power to the main generator for propulsion of the locomotive. The total horsepower thus produced is referred to as Engine Horsepower.

DIESEL LOCOMOTIVE HORSEPOWER

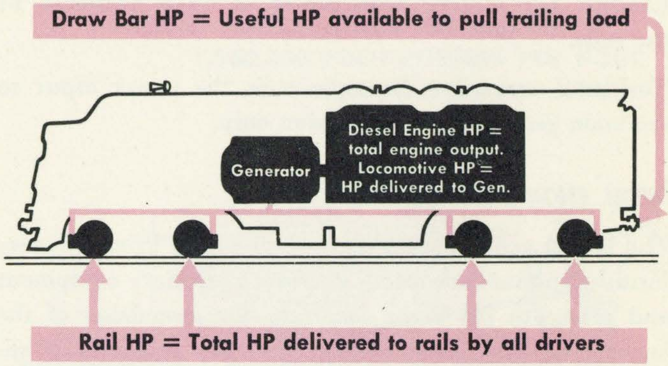
The power delivered by the Diesel engine to the main generator for propulsion of the locomotive is commonly referred to as Locomotive Horsepower or Propulsion Horsepower.

TRANSMISSION EFFICIENCY

When power is transmitted from the point of origin to the point of use, the transmission efficiency is always less than 100%. The transmission efficiency through the main generator, switching equipment, cables, traction motors and traction motor-to-axle gears averages about 82%.

RAIL HORSEPOWER

Power delivered by the wheels at the rails is equal to locomotive horsepower times transmission efficiency.



DRAW BAR HORSEPOWER

The power developed at the draw bar may be expressed as Draw Bar Horsepower and is the actual horsepower used to pull a trailing load. It is engine to generator horsepower, less electrical transmission losses and less horsepower necessary to move the locomotive only.

The formula is:

$$\text{DBHP} = (\text{Eng. to Gen. HP} \times \text{Trans. Eff.}) - \frac{(\text{Loco. Res.} \times \text{MPH})}{375}$$

Due to the fact that the formula includes "Locomotive resistance", and "MPH", it is necessary to specify the grade condition, and the speed of movement to obtain a solution.

Locomotive resistance on a straight and level track may vary from approximately 20 pounds per ton at start, to as low as 3½ pounds per ton at fairly low speeds, and may increase somewhat as speed increases. Each one per cent of grade requires an additional draw bar pull of 20 pounds per ton, and curves, journal friction, flanges, track condition and climatic conditions may cause additional locomotive resistance.

The following two examples indicate the difference in draw bar horsepower for the same locomotive, first on a straight and level track and the second on a straight track of 2% grade.

When—

Engine to Generator HP = 1500
Transmission Efficiency = 82%*
Locomotive Resistance = 3.7 pounds per ton on level track. 43.7 pounds per ton on 2% grade.
Locomotive Speed = 15.5 miles per hour
A horsepower = 375 mile pounds per hour.

$$\begin{aligned}\text{DBHP} &= (1500 \times .82^*) - \frac{(115 \times 3.7 \times 15.5)}{375} \\ &= 1230 - 17.6 \\ &= 1212.4 \text{ HP on straight and level track}\end{aligned}$$

$$\begin{aligned}\text{DBHP} &= (1500 \times .82^*) - \frac{(115 \times 43.7 \times 15.5)}{375} \\ &= 1230 - 207 \\ &= 1023 \text{ HP on 2\% grade}\end{aligned}$$

*The Transmission efficiency may be as high as 90% at some speeds, however 82% is considered a conservative figure that will meet most any condition.

This indicates that 189.4 horsepower is required for the locomotive to overcome the additional resistance of the 2% grade.

OVERALL EFFICIENCY

When draw bar horsepower for a specific locomotive is known for stated conditions, then draw bar horsepower divided by propulsion horsepower equals the overall efficiency of the locomotive.

DETERMINATION OF DIESEL LOCOMOTIVE HORSEPOWER

There are two definite requirements to be taken into consideration when determining the horsepower needed for Diesel locomotives.

1. Technical requirements—proper balance in the overall design.

2. Railroad requirements—the proper locomotive for a particular use.

Technical requirements include horsepower of the Diesel engine, method of transmitting the engine power to the wheels, weight on drivers, a suitable housing for the equipment and the speed or miles per hour that the locomotive must move trains. The formula for Locomotive Horsepower may be expressed as follows:—

$$\text{Locomotive Horsepower} = \frac{\text{Miles per hour} \times \text{Tractive Effort}}{375 \times \text{Transmission Efficiency}}$$

Since this formula contains Miles per Hour and Tractive Effort, it is necessary to specify what those two factors should be in a particular railroad application before satisfactory locomotive horsepower can be determined.

FREIGHT LOCOMOTIVE

Main line freight requires the largest number of locomotives with the greatest amount of tractive effort of any of the various types of railroad service.

With steam locomotives, variations in horsepower and tractive effort were achieved with different sizes and characteristics of single locomotives. Under extreme operating conditions, locomotives were double-headed (two locomotives in tandem each with separate crews) and/or often provided with helpers (again separate locomotives with crews) either in the middle or at the end of the freight train. Railroads customarily maintain several sizes of steam freight locomotives for various types of main line freight service depending upon grades, traffic density, and time-table requirements.

For increased flexibility and economy of both operation and production, Diesel locomotives have been built in units which can be operated in multiple from one control cab thus providing multiples of horsepower and tractive effort to cover every reasonable operating requirement.

Maximum horsepower is required during, acceleration, for fast movement of trains, and for heavy pulling at economical speeds over ruling grades. Of these three basic requirements, the operation over ruling grades is probably the most important in practical railroading.

The determination of the horsepower requirements of individual units in heavy duty freight service was made originally by relating the horsepower of engines available for railroad application to the type of service performed by various sizes and types of steam freight locomotives.

With existing strength of draw bars of freight cars, length of rail sidings, average ruling grades, and other limiting factors, the maximum requirements for locomotive tractive effort varies from 160,000 to 210,000 pounds and minimum locomotive speeds vary from 8 to 12 miles per hour over ruling grades. In some instances where the higher minimum speeds are desired it will be necessary to reduce the trailing load, thereby reducing the required tractive effort.

The tractive effort capabilities of Diesel locomotives are determined by the weight of the locomotive on its driving wheels and the thermal limit of its traction motors. At full throttle there is a speed below which a given locomotive should not be operated over prolonged periods, because below this speed the amperage used by the traction motors will produce heat that eventually will damage the machine. As the weight of locomotive units has approached the safe operating limits of conventional wheels and axles,

and as improvements have continued in traction motor cooling and insulation, the minimum speed now tends to be determined more by locomotive wheel slip than by traction motor limitations. The ability of the wheels to stick to the rails (adhesion) depends upon rail conditions. Dampness, water, leaves, rust, ice, frost and oil will cause the rails to be slippery.

When the required tractive effort is 160,000 pounds and the required speed in miles per hour is known, then by use of the following formulae, the required locomotive horsepower may be determined.

Horsepower Required to Provide 160,000 pounds Tractive Effort at Various Speeds

$$\frac{\text{MPH} \times 160{,}000}{308} = \text{H.P.}$$

MPH	H.P.	MPH	H.P.
6.0	3,120	11.5	6,000
7.0	3,640	12.0	6,240
8.0	4,160	12.5	6,500
9.0	4,680	13.0	6,760
9.5	4,940	13.5	7,020
10.0	5,200	14.0	7,280
10.5	5,460	14.5	7,540
11.0	5,720	15.0	7,800

Tractive effort in the 200,000 pound range is seldom required except for starting and for negotiating ruling grades at relatively low speeds. Traffic density usually determines the minimum allowable speed on ruling grades. To prevent delays and congestion, customary minimum speeds are somewhere between 8 and 12 miles per hour.

Where lower speeds are permissible, a tractive effort of 210,000 pounds can be provided over the same speed range with increased horsepower or at a lower speed with the same horsepower.

Horsepower Required To Provide 210,000 pounds Tractive Effort at Various Speeds

$$\frac{\text{MPH} \times 210{,}000}{308} = \text{H.P.}$$

MPH	H.P.	MPH	H.P.
6.0	4,086	10.5	7,150
6.5	4,426	11.0	7,491
7.0	4,767	11.5	7,831
7.5	5,107	12.0	8,172
8.0	5,448	12.5	8,512
8.5	5,788	13.0	8,853
8.8	6,000	13.5	9,193
9.0	6,129	14.0	9,534
9.5	6,469	14.5	9,874
10.0	6,810	15.0	10,215

Thus 6000 horsepower will provide the maximum Tractive Effort requirements of from 160,000 pounds to 210,000 pounds at minimum speeds of from 11.5 to 8.8 miles per hour. The total horsepower can be readily divided into four units of 1500 hp each. Additional horsepower per unit will only have the effect of increasing these minimum speeds proportionately.

When traffic conditions are such that the total locomotive of 6000 horsepower is not needed, the individual units of 1500 horsepower may be used singly or in combinations of 3000 or 4500 horsepower. The resulting flexibility provides ample horsepower coverage for practically any railroad motive power requirement for starting and operating over ruling grades, at speeds consistent with railroad schedules and traffic demands. From a practical standpoint, the need for special-purpose types of freight locomotives is completely eliminated with this range of horsepower options.

When horsepower is increased the speed in miles per hour of the locomotive will be increased proportionately. Maximum locomotive speed will not be increased because it is limited by the safe rotational speed of the traction motor armature.

For example, should the horsepower be increased from 1500 to 1750, the speed in miles per hour, with the same trailing load, would be increased by 1.16 times the original speed.

$$\frac{1750}{1500} = 1.16$$

PASSENGER LOCOMOTIVE

Horsepower requirements in high speed streamline passenger service are primarily determined by the weight and number of cars to be pulled and the maximum speed in miles per hour to be attained. As the speed of a given train is increased, the power requirement increases and the useful power output of the Diesel locomotive decreases. This may be expressed in terms of draw bar horsepower requirement of the train only and draw bar horsepower ability of the locomotive at various speeds. The additional power requirements imposed by grades, curves, journal friction, flanges, track and climatic conditions will be eliminated by considering the following operation to be upon straight and level track where normal conditions exist.

Modern lightweight streamlined passenger cars weigh about sixty-five tons and a train may consist of from four to twenty such cars depending primarily upon traffic conditions, speed and grades.

The horsepower required to pull such a train of cars only, may be computed by the use of the following formula:—

$$\text{DBHP} = \frac{\text{Resistance} \times \text{weight} \times \text{number cars} \times \text{MPH}}{375}$$

Resistance = Rolling resistance in pounds per ton.

Weight = Tons per car.

The total resistance in pounds per ton of car weight with an auxiliary load of 20 horsepower per car for lighting and air conditioning may be determined from Table I.

TABLE I

Rolling Resistance—65 Ton Streamlined Passenger Cars with 20 HP Auxiliary Load

MPH	20	40	60	80	90	100	110	120
Car Res. #/Ton	3.85	4.89	6.23	7.86	8.80	9.80	10.87	12.02
20 HP Aux.	5.76	2.87	1.92	1.44	1.27	1.15	1.06	.97
Total Pounds/ton	9.61	7.76	8.15	9.30	10.07	10.95	11.93	12.99

By the use of the above formula and Table I, the draw bar horsepower requirements of eight trains traveling at eight representative speeds have been arranged for easy reference in Table II. For example, a seventeen car train traveling at 40 miles per hour requires a draw bar pull of 916 horsepower. At 110 miles per hour, this same train requires a draw bar pull of 3860 horsepower.

DRAW BAR HORSEPOWER REQUIREMENTS on straight and level track

65 Ton Streamlined Passenger Cars 20 HP Aux. Load

TABLE II

CARS IN TRAIN

MPH	4	6	8	10	12	15	17	20
20	133	199	266	333	398	498	566	666
40	215	322	430	538	644	806	916	1076
60	338	508	676	847	1016	1268	1440	1694
80	515	772	1030	1288	1544	1930	2190	2576
90	630	945	1261	1576	1890	2364	2680	3152
100	758	1138	1516	1897	2276	2845	3225	3794
110	919	1362	1838	2270	2724	3400	3860	4540
120	1080	1620	2160	2700	3240	4050	4590	5400

These calculations do not include allowance for rapid acceleration to the given speed. If rapid acceleration to a certain speed is desired, additional horsepower must be provided, which will naturally result in a still higher ultimate speed. A simple rule-of-thumb that may or may not be sufficiently accurate, is to provide enough draw bar horsepower to move the train at least ten miles per hour faster than the required top speed.

The draw bar horsepowers of typical streamlined high speed Diesel passenger locomotives at the above passenger train speeds provide a means of determining the required locomotive to move the trains at such speeds.

The draw bar horsepower of a Diesel locomotive may be determined for any given speed by formula when the engine to generator horsepower, transmission efficiency and locomotive rolling resistance are known.

$$\text{DBHP} = (\text{Eng. to Gen. HP} \times \text{Trans. Eff.}) - \frac{(\text{Loco. Res.} \times \text{MPH})}{375}$$

Engine to generator horsepower times transmission efficiency indicates the horsepower at the rails. Locomotive resistance expressed in pounds times miles per hour divided by 375 represents the horsepower required to move the locomotive only. The horsepower required to move the locomotive subtracted from the rail horsepower provides the useful horsepower of the locomotive commonly known as Draw Bar Horsepower.

For sake of illustration a General Motors high speed E8 passenger locomotive unit has been selected as typical of the type used to pull many of America's famous passenger trains. Power is supplied by two Diesel engines providing 2250 horsepower to the generators for traction purposes. These units have six wheel trucks with two-thirds of the weight on drivers.

Draw bar horsepower values for locomotives consisting of one, two or three such units at eight speeds are listed in Table III.

TABLE III

DBHP—E8 Diesel Locomotive Units

Straight and Level Track

MPH	1 Unit 2250 HP	2 Units 4500 HP	3 Units 6750 HP
20	1765	3575	5371
40	1810	3621	5458
60	1742	3510	5291
80	1530	3193	4792
90	1394	2997	4582
100	1230	2770	4272
110	1051	2505	3912
120	837	2205	3492

Many present day high speed passenger trains consist of fifteen to twenty cars and may be expected to reach top speeds of from ninety to one hundred and ten miles per hour. A seventeen car train traveling at 110 miles per hour requires a draw bar horsepower of 3860 (Table II). Referring to Table III, a three unit locomotive will produce 3912 horsepower at the draw bar at 110 miles per hour and will move the train at an ultimate speed of slightly over 110 miles per hour.

If the top speed can be reduced to 90 miles per hour, the required draw bar horsepower will then be 2680, (Table II). This horsepower can be supplied by a two unit locomotive which provides 2997 horsepower at 90 miles per hour.

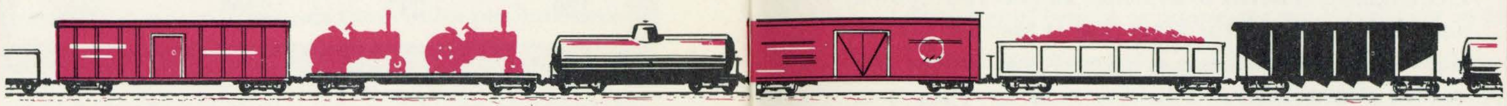
A two unit locomotive at 90 miles per hour has sufficient horsepower at the draw bar to pull two additional cars or to provide much more rapid acceleration for seventeen cars to 90 miles per hour.

This same train of seventeen cars can be pulled in medium speed operation by the use of one unit. At sixty miles per hour, a single unit will develop a draw bar horsepower of 1742 (Table III), and at this same speed, the train would require a draw bar horsepower of 1440 (Table II).

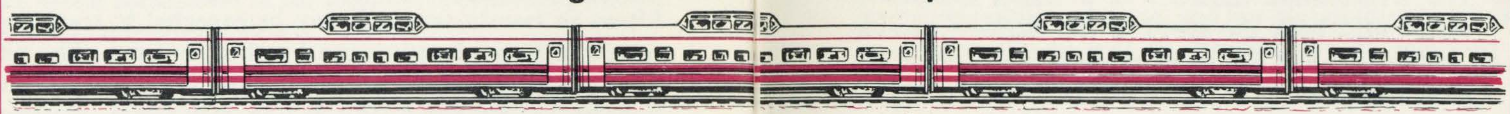
A single unit in high speed operation can pull six cars at 100 miles per hour. In fact there are so many combinations of cars and speeds that may be obtained with one, two or three unit locomotives of this type that it becomes difficult to even imagine a condition that cannot be economically and practically met.

For those interested in practical operation where grades are involved, 20 pounds per ton of weight should be added to car and locomotive resistance figures for each one per-cent of grade.

HP requirements are the same



89 freight cars @ 40 miles per hour



17 passenger cars @ 100 miles per hour

17-65 ton passenger cars @ 100 miles per hour require 3225 H.P. (Table II, pg. 17)

50-ton freight car resistance @ 40 m.p.h. = 6.8 lbs. per ton

$$DBHP = \frac{\text{res.} \times \text{wt.} \times \text{no. cars} \times \text{m.p.h.}}{375}$$

$$= \frac{6.8 \times 50 \times 1 \times 40}{375}$$

$$= 36.26 \text{ DBHP per car}$$

$$3225 \div 36.26 = 89 \text{ cars}$$

SUMMARY

1. The word "horsepower", originated early in the eighteenth century, has become the universally accepted term for determining the rate of doing work.

2. Contrary to general belief, a horsepower is equal to about one and one half times the work-ability of the average horse.

3. A uniform method of horsepower rating of the various types and kinds of locomotives now in existence is not presently available to make comparisons of their abilities.

4. The total useful power delivered by the Diesel locomotive engine is referred to as Diesel Engine Horsepower and that portion of the total that is used for propulsion of the locomotive is referred to as Diesel Locomotive Horsepower.

5. The transmission efficiency of a Diesel locomotive varies with both the speed of the engine-generator combination and the speed in miles per hour of the locomotive.

6. Rail Horsepower is the power delivered by the wheels at point of contact with the rails and Draw Bar Horsepower is the useful power of the locomotive that is available to pull a train or trailing load.

7. The horsepower of a Diesel locomotive is only one of the many technical requirements that must be taken into consideration if the locomotive is to properly meet railroad requirements.

8. The horsepower of freight locomotives is primarily used for pulling heavy loads at slow speeds.

9. In passenger locomotives, horsepower is primarily used to pull lighter loads at higher rates of speed.

10. A few passenger cars will require as much horsepower to travel at speeds of over one hundred miles per hour as a long freight train will require when traveling at fifty or sixty miles per hour.

11. The now commonplace practice of supplying necessary locomotive horsepower on a unit basis provides a motive power flexibility unknown in steam practice. Units may be used singly or coupled together to provide the proper horsepower for practically any combination of freight or passenger car trains now in use.

The ability of a Diesel locomotive—as with any piece of machinery—is the result of a compromise of its essential characteristics. Speed, durability, ease of maintenance, interchangeability of parts, and low cost of operation must be considered—as well as Horsepower—in achieving a balance design for practical railroad operation.

Since it is impossible in a short booklet of this kind to present performance information applicable to a specific railroad, Electro-Motive maintains a specialized group whose services are available for supplying complete performance studies, tonnage ratings, speed-distance calculations and economic studies for our equipment on any railroad. This service is available by application to our Regional Sales Offices.

GENERAL MOTORS LOCOMOTIVES

ELECTRO-MOTIVE DIVISION

General Motors Corporation **La Grange, Illinois**

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