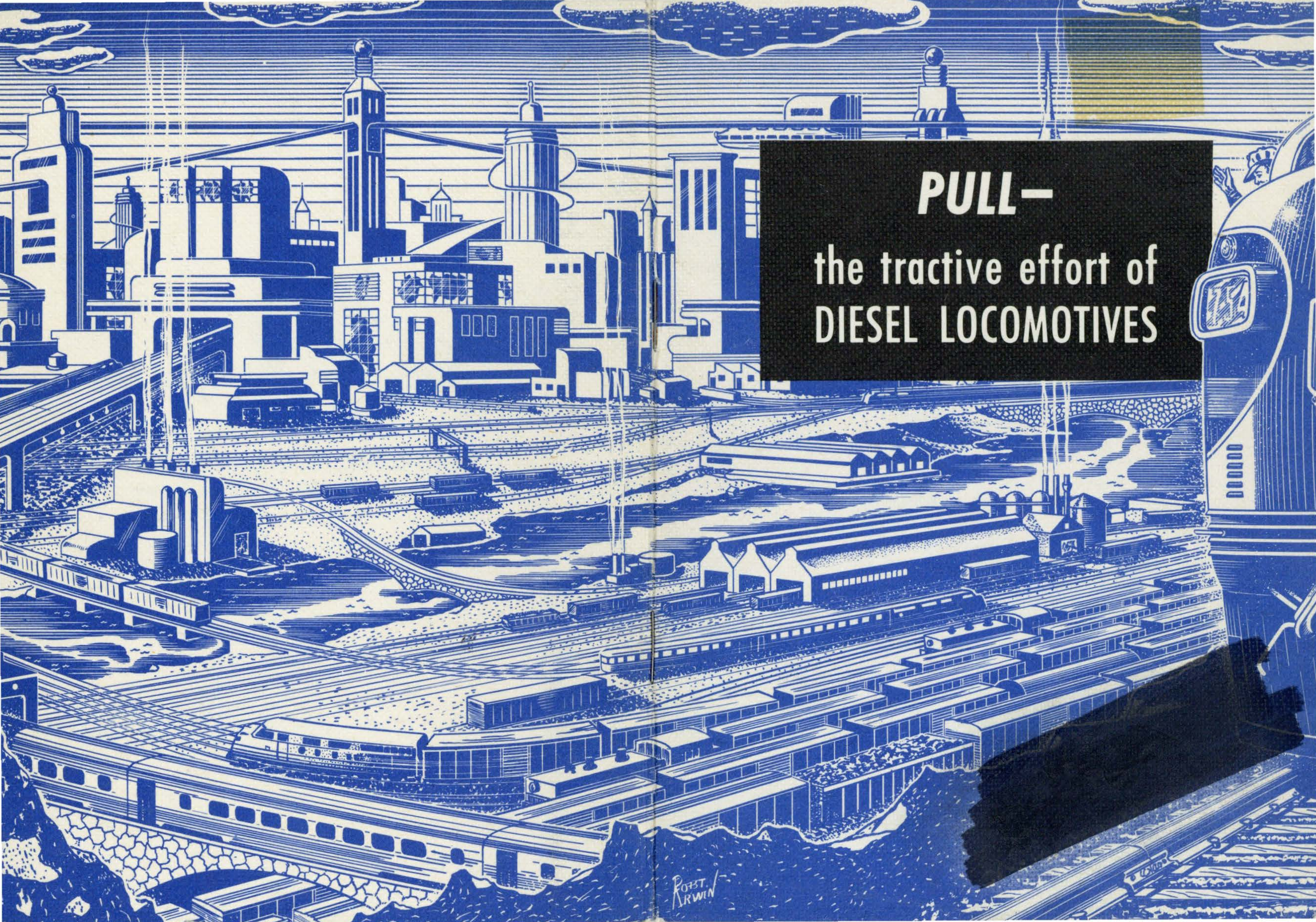
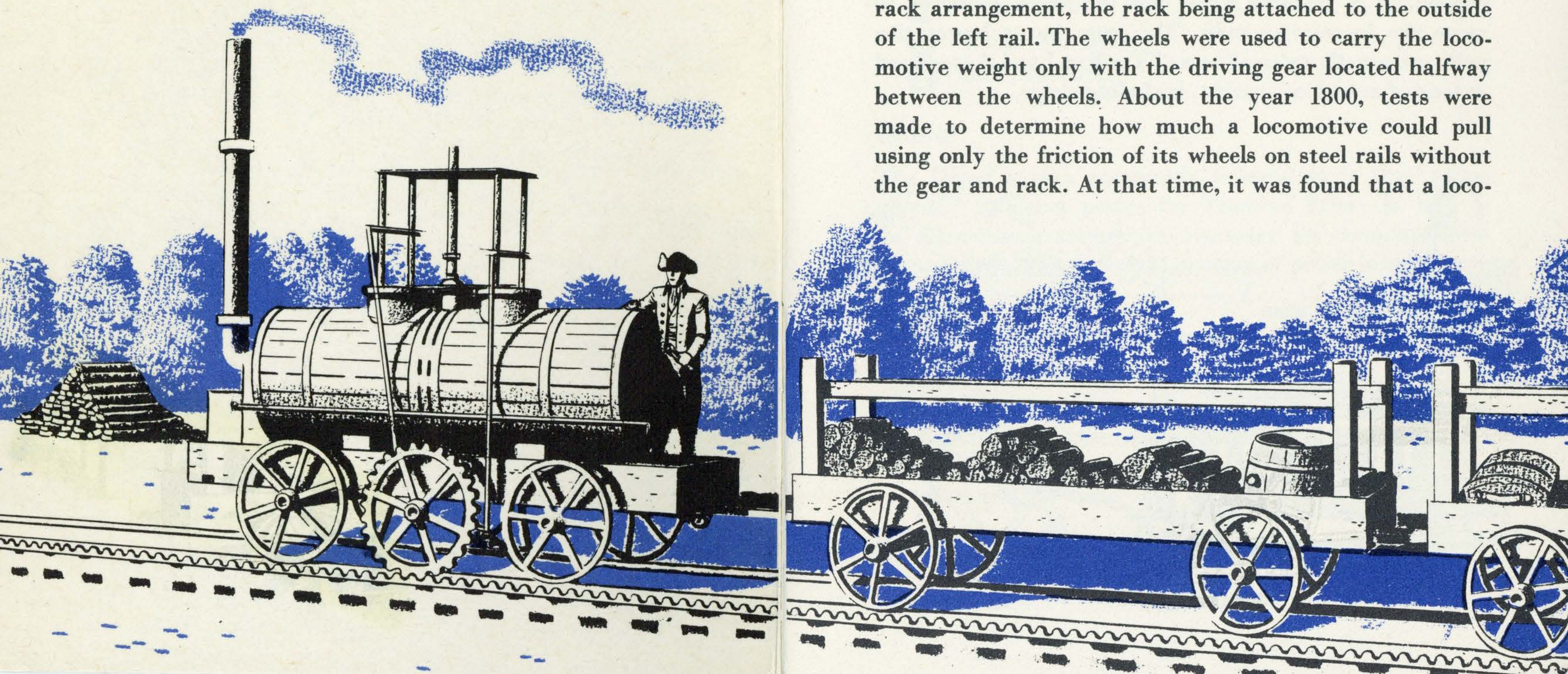
PULL–
the tractive effort of DIESEL LOCOMOTIVES



In a young and growing industry there is often a lack of simplified, authentic literature pertaining to the use of the product. To a certain extent that has been true as far as Diesel locomotives are concerned. As a step in providing the kind of information that will be helpful to a broad group of users and operators, we at Electro-Motive have prepared this booklet. The subject matter is based on our experience in producing and observing the operation of more than five million Diesel horsepower on American railroads. Other booklets on problems incident to Diesel railroad operation will appear from time to time.

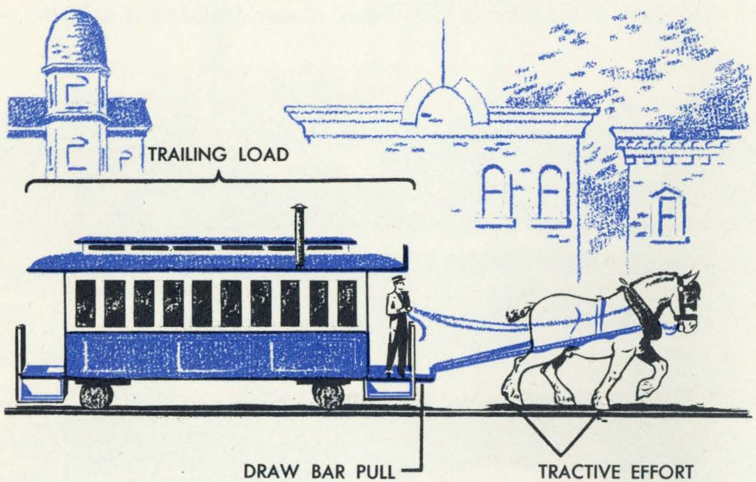


THE ability of Diesel locomotives to pull heavy loads at fast speeds has become widely recognized. But just how much a particular Diesel locomotive can pull over a certain section of track and at what speeds are questions the answers to which involve many factors. An explanation of these factors will promote a better understanding of Diesel locomotive operation.

DEFINITIONS

When steam locomotives were first used in England, it was believed necessary to drive the locomotive by a gear and rack arrangement, the rack being attached to the outside of the left rail. The wheels were used to carry the locomotive weight only with the driving gear located halfway between the wheels. About the year 1800, tests were made to determine how much a locomotive could pull using only the friction of its wheels on steel rails without the gear and rack. At that time, it was found that a locomotive with sufficient horsepower to spin the wheels exerted a pull in pounds of about one-fourth of the weight on its driving wheels without wheel slip. This turning force produced at the rails by the driving wheels has been referred to as "Tractive Force," "Tractive Effort," "Tractive Ability" and "Tractive Power." The first two, "Tractive Force" and "Tractive Effort" are preferred, but "Tractive Effort" has been chosen herein because it is found most frequently in current railroad vernacular.

The actual pulling ability of a locomotive is commonly referred to as "Draw Bar Pull," usually expressed in pounds. It is Tractive Effort less the effort necessary to move the locomotive only. The cars that a locomotive pulls are usually referred to as "Trailing Load," expressed in tons of actual car weight, including cargo.



Each of these terms has its part in describing the overall performance of a Diesel locomotive and each has a definite relationship to the other.

TRACTIVE EFFORT

The Tractive Effort developed by a Diesel locomotive depends upon six principal factors:

1. Horsepower of the engine.
2. Ability of the main generator.
3. Ability of traction motors.
4. Gear ratio.
5. Weight on drivers.
6. Rail condition.

ENGINE

The Diesel engine, commonly referred to as the "prime mover," furnishes power for Tractive Effort as well as for the various accessories necessary for complete locomotive operation. A typical division of power is as follows:

	Horsepower
Rated power into generator for propulsion.	1500
Power required for driving auxiliary equipment which includes auxiliary direct current generator, radiator cooling fans, traction motor blowers, main generator cooling blower and air compressor.	125
Rated power output of engine.	1625

Governor and load-control devices may be used to keep the engine within specified revolutions per minute limits and to regulate the generator load on the engine. This combined action can produce a balanced engine output which maintains maximum engine efficiency and horsepower throughout the entire operating range.

The horsepower of the engine determines the possible Tractive Effort that a locomotive can develop at the rims of the driving wheels *if conditions were such that the wheels could not slip.* A rough and ready formula of Tractive Effort that applies to all Diesel locomotives under such assumed conditions is as follows:

$$\text{Tractive Effort (in pounds)} = \frac{\text{Engine Horsepower} \times 308}{\text{Miles per Hour}}$$

By the use of the above formula, it can be shown that—by placing an engine of greater horsepower in a given locomotive with sufficient Weight on Drivers to avoid wheel slip—Tractive Effort will be increased at the same speed, or speed will be increased with the same Tractive Effort.

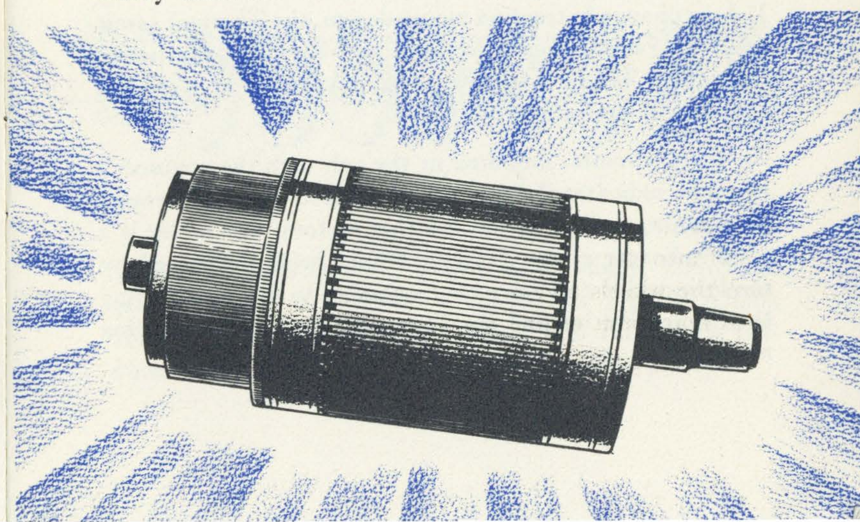
MAIN GENERATOR

The main generator is the first step in the transmission of the engine power to the wheels. It converts mechanical power into electrical energy used by the traction motors to turn the wheels and must have ample capacity to transform maximum engine horsepower into electrical energy.

Generators may be designed to produce an electrical output of low voltage and high amperage or high voltage and low amperage. Either one of these designs may transfer mechanical power into electrical energy satisfactorily.

TRACTION MOTORS

The traction motors make up the second step of the transmission system. Their function is to transform the electrical energy of the generator into mechanical force to turn the locomotive wheels. The traction motors must be of heavy duty construction but, as with all electrical devices, they have certain limitations. The rotating element in a traction motor, through which the drive shaft is rigidly mounted, is an armature. The armature is composed of a laminated steel core around which are wound *insulated* copper coils connected to a commutator. The flow of electric current from the generator passes into the armature through carbon brushes in contact with the commutator. In order to turn a traction motor armature under heavy load, the electric current (amperes) must be very



high. Amperes produce heat as well as power. Naturally, then, there is a limit to the number of amperes that the armature coils can safely carry without injury to the insulated winding from overheating. This is called "Thermal Limit" and is a certain number of amperes for continuous operation depending upon the materials used for insulation and the extent of cooling of the motor.

It so happens that when the traction motor is using a sufficient number of amperes to approach the Thermal Limit, the armature is turning at a certain definite number of revolutions per minute with a given load. Due to the fact that the armature shaft is geared to the axle, this armature speed corresponds to a certain locomotive speed in miles per hour. This is the minimum speed at which the locomotive may be continuously operated because, below this speed, the traction motors will use an amperage in excess of the Thermal Limit resulting in heat damage to the traction motor coils.

If, by a change in traction motor design, the Thermal Limit could be raised, then a locomotive with the same horsepower and Weight on Drivers could pull more tonnage but at a slower continuous speed.

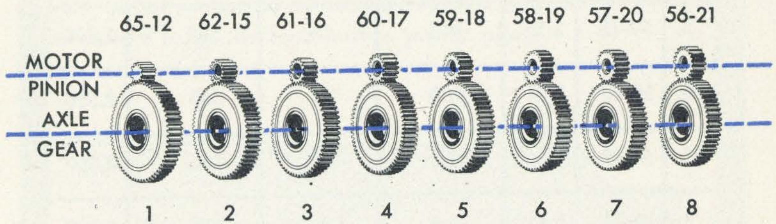
An electric meter, mounted in the cab with the engineer's controls, indicates the number of amperes flowing through the windings of one of the traction motors. The meter is a good indicator of the Tractive Effort being developed by the locomotive and warns the engineer to avoid operating the locomotive beyond the Thermal Limit of the traction motors.

Maximum locomotive speed is limited by the safe rotational speed of the traction motor armature. This is due to the fact that the centrifugal force generated at the outer rim of the armature must be limited to prevent damage to the armature windings and banding. The maximum safe revolutions per minute of the armature may be expressed in maximum miles per hour of locomotive speed.

GEAR RATIO

The most practical way to drive Diesel locomotive wheels is to rigidly mount two wheels on an axle and gear the axle to a traction motor. Within limits, various sizes of gears may be provided to produce alternative gear ratios.

GEAR RATIO CHART



Within a given traction motor speed range, high ratio gears produce a locomotive which has greater pulling ability but at a slower speed range. Low ratio gears produce higher speeds with lower pulling ability.

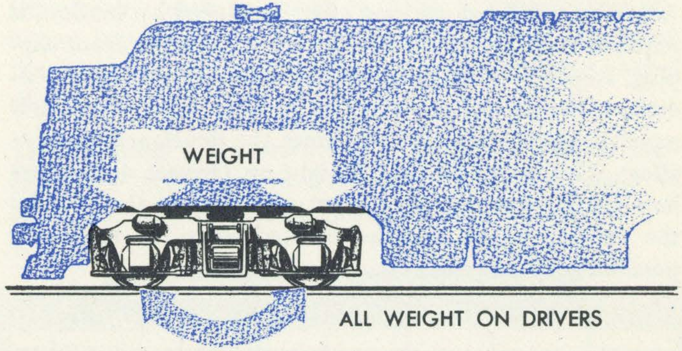
The following table indicates the minimum and maximum speed ratings for typical gear ratios at full throttle operation.

GEAR RATIO COMPARISONS*

	Axle-Pinion Gears	Ratio	Locomotive M. P. H.		Motor RPM	
			Minimum Continuous	Maximum	Minimum Continuous	Maximum
1.	65-12	5.41	12.0	50	545	2,500
2.	62-15	4.13	15.5	65	545	2,500
3.	61-16	3.81	17.0	71	545	2,500
4.	60-17	3.53	18.5	77	545	2,500
5.	59-18	3.28	19.5	83	545	2,500
6.	58-19	3.05	21.0	89	545	2,500
7.	57-20	2.85	22.5	95	545	2,500
8.	56-21	2.66	24.5	102	545	2,500

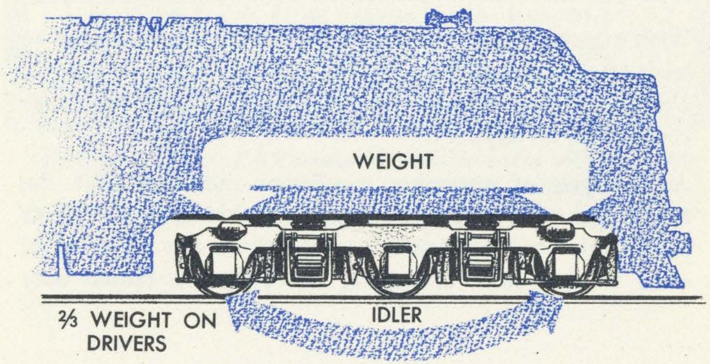
TABLE I

**F-3 Freight-passenger locomotive*



WEIGHT ON DRIVERS

Weight on Drivers refers to that portion of the entire locomotive weight which is supported by the wheels that are driven by the traction motors. On some locomotives all of the weight is carried by the driving wheels and on others, part of the weight is carried by idler wheels which receive no power from the locomotive power plant.



Adhesion, a grip or sticking effect produced by friction, is required to prevent the wheels of a locomotive from slipping. Repeated tests have proven, that under normal conditions, the weight necessary to prevent wheel slipping is equal to approximately four times the developed tractive effort. This indicates that Weight on Drivers determines how much of the tractive effort produced at the rails by the driving wheels can be utilized with the minimum possibility of slipping.

A rule of thumb formula for maximum Tractive Effort is:

$$\text{Tractive Effort} = \frac{\text{Weight on Drivers}}{4}$$

When using this formula in a practical way it is assumed that the locomotive has the ability to produce such Tractive Effort and that rail conditions are such as to sustain such effort. Such conditions may or may not be true.

RAIL CONDITIONS

With a given weight on them, 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.

An analysis of operating conditions indicates that the usable adhesion factor may vary from 25% to as low as 5%. With very favorable conditions or the addition of sand to fair rail conditions, the adhesion factor may

temporarily reach as much as 35%. A conservative adhesion factor of 22% is considered to be the maximum that can be used generally without excessive wheel slipping.

The following table based upon Weight on Drivers indicates the starting Tractive Effort and percentage of adhesion, utilized to produce such Tractive Effort.

TRACTIVE EFFORT COMPARISONS*

	Axle-Pinion Gears	Ratio	Max. MPH	Tractive Effort Starting	% Adh. Utilized Starting	Tractive Effort Continuous	% Adh. Utilized Continuous
1.	65 - 12	5.41	50	67,000	29.1	42,400	18.4
2.	62 - 15	4.13	65	51,500	22.4	32,500	14.0
3.	61 - 16	3.81	71	47,500	20.6	30,000	13.0
4.	60 - 17	3.53	77	43,500	18.9	27,500	11.6
5.	59 - 18	3.28	83	41,000	17.8	25,600	11.1
6.	58 - 19	3.05	89	38,000	16.5	24,000	10.4
7.	57 - 20	2.85	95	35,000	15.2	22,500	9.7
8.	56 - 21	2.66	102	33,000	14.3	21,000	9.1

TABLE II

**Based on a 115 ton F-3 Passenger-Freight locomotive with 40" wheels.*

NOTE—It will be observed that in the case of gear ratios 1 and 2 favorable rail conditions must exist to achieve maximum starting tractive effort.

DRAW BAR PULL

The actual pulling ability of a locomotive, Draw Bar Pull, is Tractive Effort less the effort necessary to move the locomotive itself.

Various actual tests have indicated that it requires from 16 to 20 pounds of pull per ton to start the average freight car under favorable conditions of temperature and rails. A locomotive with roller bearings will start with somewhat less effort but 20 pounds per ton will be used for simplification. At this rate, a 115 ton locomotive requires 20 x 115 or 2,300 pounds of the total Tractive Effort to start itself. The starting Draw Bar Pull is starting Traction Effort minus 2,300 pounds.

DRAW BAR PULL COMPARISONS*

	AXLE-PINION GEARS	STARTING TE		LOCO LOAD		D. B. PULL (lbs.)
1.	65-12	67.000	–	2,300	=	64,700 lbs.
2.	62-15	51,500	–	2,300	=	49,200 lbs.
3.	61-16	47,500	–	2,300	=	45,200 lbs.
4.	60-17	43,500	–	2,300	=	41,200 lbs.
5.	59-18	41,000	–	2,300	=	38,700 lbs.
6.	58-19	38,000	–	2,300	=	35,700 lbs.
7.	57-20	35,000	–	2,300	=	32,700 lbs.
8.	56-21	33,000	–	2,300	=	30,700 lbs.

TABLE III

**Based on 115 ton F-3 Passenger-Freight locomotive with 40" wheels.*

TRAILING LOAD

The average weight of a freight car including both loads and empties is considered to be approximately 40 tons. On a basis of 20 pounds per ton, it requires 40 x 20 or 800 pounds of Draw Bar Pull to start the average freight car on a level track. A 1500 H.P. locomotive with 62/15 gear ratio develops 49,200 pounds Draw Bar Pull at start. Therefore, 49,200 divided by 800 equals 61.

This indicates that a Trailing Load of approximately 61 cars can be started on a straight and level track without locomotive wheel slipping, under favorable conditions and without taking slack.

Conditions change rapidly when the train is moving, even at comparatively low speeds. The approximate minimum continuous speed of the 62/15 geared locomotive is 15.5 miles per hour.* The Tractive Effort at this speed is 32,500 pounds. The Tractive Effort required by the locomotive alone at 15.5 miles per hour is 440 pounds. Then 32,500 minus 440 leaves 32,060 pounds Draw Bar Pull. A 40 ton freight car requires approximately 5 pounds per ton Draw Bar Pull at 15.5 miles per hour, therefore 5 x 40 equals 200 pounds Draw Bar Pull. Total Draw Bar Pull of 32,060 divided by 200 indicates that the locomotive could pull a Trailing Load 160 freight cars averaging 40 tons each at 15.5 miles per hour on a straight and level track under ideal conditions. However, since in this illustration the locomotive could only start 61 cars, *it* would not be called upon to pull 160 cars in actual operation.

**In practice, actual minimum speed will be controlled by the permissible amperage shown on the meter in the engineer's cab.*

APPLICATION

But we must remember that in practical railroading the ideal conditions of a straight and level track very rarely or ever exist throughout an entire division. Load conditions usually require locomotives having more horsepower than is available in one unit, therefore for those interested in details, the following is a more nearly actual condition.

ONE DIVISION

180 miles

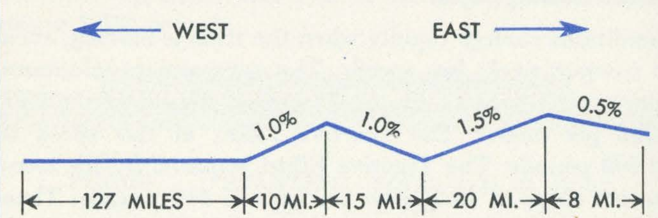


TABLE IV

Eastbound:

Ruling grade—20 mi. of 1.5%

Locomotive —2 units—62/15 gear ratio—3000 HP—230 tons.

Minimum continuous speed 15.5 MPH

Tractive Effort @ 15.5 MPH = 32,500 lbs. per unit

Tractive Effort required by a two unit locomotive to move itself @ 15.5 MPH on level track equals 850 lbs.

A grade requires an additional 20 pounds per ton per 1%* or 30 pounds per ton for a 1½% grade. 230 times 30 pounds equals 6900 pounds. Then 850 pounds plus 6900 pounds equals a total of 7750 pounds of Tractive Effort for the locomotive alone. Two units will produce a total of 65,000 pounds Tractive Effort. 65,000 minus 7750 equals 57,250 pounds Draw Bar Pull available to pull the train.

A freight car requires approximately 5 pounds Draw Bar Pull per ton at 15.5 miles per hour on level track. The 1½% grade will require 30 pounds per ton additional or a total of 35 pounds per ton. An average 40 tons car will then require 40 times 35 or 1400 pounds of Draw Bar Pull per car. The locomotive will produce 57,250 pounds Draw Bar Pull, therefore, 57,250 divided by 1400 equals 41 cars. The Trailing Load then becomes 40 x 41 or 1640 tons.

**Curves, journal function, flanges, track condition and air or wind may cause additional train resistance.*

DETAILS OF THE EASTBOUND RUN

Locomotive..........3000 HP—62/15 Gear Ratio

Trailing Load........1640 tons—41-40 ton cars

Level Track Speed....54 MPH

1% Up Grade Speed..20.5 MPH

1½% Up Grade Speed 15.5 MPH

Down Grade Speed...65 MPH (or railroad restriction)

Westbound:

Ruling Grade........15 miles of 1%
Locomotive..........Same

The locomotive requires 850 pounds Tractive Effort on level track. A 1% grade requires 20 pounds times 230 or 4600 pounds Tractive Effort. Total Tractive Effort required by the locomotive on a 1% grade equals 4600 plus 850 or 5450 pounds. The total tractive effort developed by the locomotive, 65,000 pounds minus 5450 pounds, equals 59,550 pounds Draw Bar Pull available to pull the train.

The freight cars require 5 pounds per ton on level track and an additional 20 pounds for the 1% grade or a total of 25 pounds per ton. Assuming the same 40 ton cars times 25 pounds per car; 59,550 divided by 1000 equals 59 cars. Trailing load equals 40 tons per car times 59 or 2360 tons.

DETAILS OF THE WEST BOUND RUN

Locomotive..........3000 HP—62/15 gear ratio

Trailing Load........2360 tons

Level Track Speed....45 MPH

0.5% Up Grade Speed 24 MPH

1% Up Grade Speed..15.5 MPH

Down Grade Speed...65 MPH (or railroad restriction)

SUMMARY

1. Tractive Effort is the pulling force produced at the rails by the driving wheels of a locomotive.

2. The actual pulling ability of a locomotive is "Draw Bar Pull" which is Tractive Effort less the effort to move the locomotive only. The load pulled is called "Trailing Load."

3. Usable Tractive Effort depends upon six factors.

   1. Horsepower of the engine
   2. Ability of the Main generator
   3. Ability of traction motors
   4. Gear Ratio
   5. Weight on drivers
   6. Rail conditions

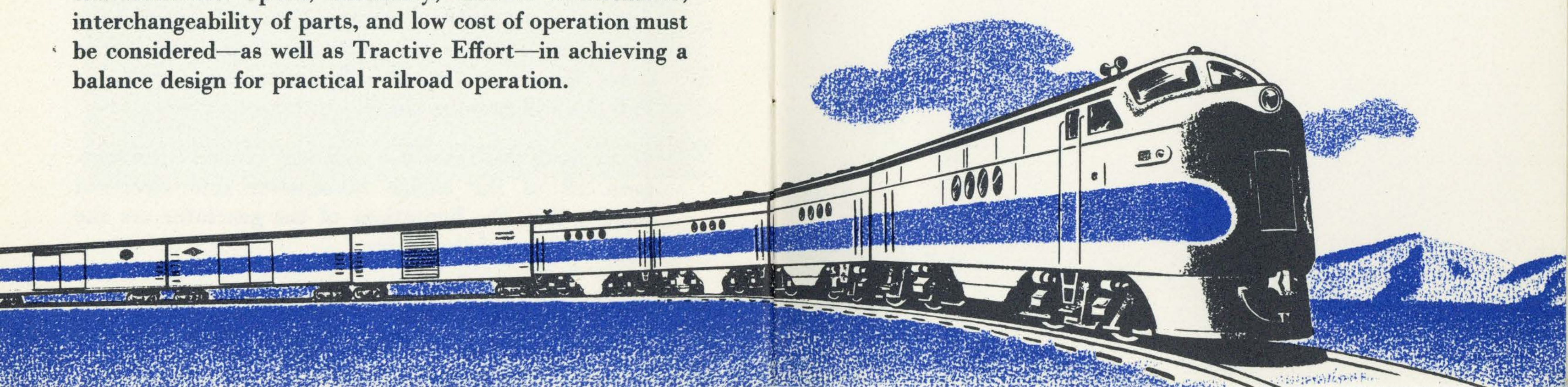
4. The Diesel engine is the prime mover. To utilize the full horsepower of the engine for pulling ability, the locomotive must have Weight on Drivers at least four times the developed Tractive Effort. Engine horsepower which produces Tractive Effort in excess of four times Weight on Drivers will not increase Draw Bar Pull but will increase speed.

5. If the main generator has sufficient capacity to transform all of the engine horsepower into electrical energy, then the limitations of the generator are the same as those of the engine.

6. Traction motors perform all of the work of applying the power of the engine to the locomotive wheels. One of the controlling limitations of the traction motors is the heat generated by electrical current (amperes). Such heat limitations are called Thermal Limits which, because of fixed gears, can be expressed in minimum speeds for continuous locomotive operation. If, by a change in traction motor design, the Thermal Limit can be raised, then a locomotive with the same horsepower and Weight on Drivers could pull more tonnage but at a slower continuous speed. The other controlling limitation is the safe rotational speed of the armature, which determines the maximum speed of the locomotive.
7. Within a given traction motor speed range, high gear ratios produce a locomotive which has greater pulling ability, but at lower speeds. Low gear ratios produce higher speeds with less pulling ability.

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 Tractive Effort—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

LITHO IN U. S. A.